Woods Hole Oceanographic Institution

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Technical Report

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Cyclic Fatigue Testing of Surface Mooring Hardware for the Arabian Sea Mixed Layer Dynamics Experiment

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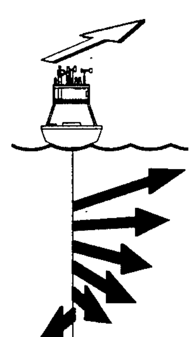

Upper Ocean Processes Group
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543 U.S.A.

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Approved for Distribution:

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Abstract

The Arabian Sea is strongly forced by monsoon winds. Surface moorings deployed in the Arabian Sea are exposed to high winds and large waves. The waves, generated by strong wind events, impose a dynamic load on all mooring components. The dynamic cycling of mooring components can be so severe that ultimate strength considerations are superseded by the fatigue properties of the standard hardware components.

Concerns about all in-line mooring components and their fatigue endurance dictated the need for an independent series of cyclic fatigue tests. The components tested included shackles of various sizes and configurations, wire rope, instrument cages, chain, and a variety of interconnecting links such as weldless sling links and end links. The information gained from these tests was used in the design of the surface moorings deployed in the Arabian Sea by the Upper Ocean Processes group of the Woods Hole Oceanographic Institution.

The results of the cyclic fatigue tests conducted in support of the Arabian Sea surface mooring design effort are presented in this report. Recommendations are made with regard to all in-line components for surface moorings where dynamic conditions might be encountered for extended periods. The fatigue test results from shackles, and sling links were compiled to generate an S/N diagram where the cyclic stress amplitude is plotted versus the number of cycles to failure. In addition the wire rope test results were compiled with historical wire rope data from US Steel to generate a S/N diagram for torque balanced 3 x 19 wire rope. These results can be used in conjunction with future design efforts.

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Section I: Introduction

Materials tests conducted on a variety of mooring hardware components produced interesting results which were needed to specify the type of hardware to be used on the WHOI surface mooring deployed in the Arabian Sea in October 1994 and April 1995. Special care was taken during the design of the Arabian Sea surface mooring since environmental conditions there are believed to be more severe than in other regions where surface moorings have been deployed in the past.

For years the efforts to investigate air–sea interaction and upper ocean variability with surface moorings have focused on regions characterized by light to moderate atmospheric forcing. Wind and wave conditions have therefore not been considered critical factors in the design process. The desire to increase the understanding of air–sea interaction processes has required the capability to make time series observations of both forcing and response in severe environments. Surface moorings must now be designed for severe environments with strong atmospheric forcing along with the steady current conditions. Waves generated by strong wind events impose a dynamic load on mooring components. Superimposed on the background static tension from the currents is an oscillating dynamic tension generated by each passing wave. The dynamic cycling can be so severe that ultimate strength considerations are superseded by the fatigue properties of the standard hardware components.

Since the environmental conditions in the Arabian Sea are generally thought to be more severe than in other regions where surface moorings have been deployed an intense mooring design effort was launched. The Arabian Sea surface mooring design study included: (1) the collection of existing current, wave, and wind data; (2) use of that data in a static and dynamic mooring design study; and (3) laboratory materials testing. The materials tests were guided by the results of the mooring design study and provided input to the choice of hardware used in the surface mooring. Of particular interest here are the results of the laboratory materials testing that was done in support of the Arabian Sea design effort.

Concerns about all in-line mooring components and their fatigue endurance dictated the need for an independent series of cyclic fatigue tests. The components tested included shackles of various sizes, configurations, and manufacturers, wire rope, instrument cages, chain, and a variety of interconnecting links such as weldless sling links and end links.

Section II: Background Information

A standard, off-the-shelf, oceanographic surface mooring design does not exist. The surface mooring, like the subsurface mooring, is a tool that must be tailored every time it is used to meet the requirements for which it is intended. The first order requirement is that it must remain on station for the duration of the intended deployment. From that basic goal one can begin to specify the desired performance criteria (i.e., inclination, tensions, watch circle) all of which are affected by the expected environmental conditions (i.e., wind, wave, and current conditions), water depth, the number of instrument packages to be deployed, instrument sizes and weights, their location in the water column and mooring component sizes, weights and lengths. The greatest unknown in the design effort is usually the expected environmental conditions.

Historically the ocean current in the region where a mooring was to be deployed was the primary forcing factor considered in the design process. Mooring performance under the influence of a steady state current has been modeled. If the model is exercised by several current profiles the performance of the mooring can be evaluated under a range of conditions. Typically three current profiles are used to evaluate the static performance of the mooring. One profile depicts the normal conditions expected for the area. This is called the design current profile. The mooring is designed to meet all of the performance specifications when subjected to the design current profile. A second current profile used in the design process consists of the most severe currents either previously observed or anticipated for the site. This is called the survival current profile. The mooring must be able to survive (i.e., not break or part) when subjected to a survival current profile. The mooring performance criteria are temporarily overlooked under such conditions as long as the mooring does not break. The third profile used in the design process is a low current condition. The purpose of examining mooring performance in low currents is to check the inclinations of individual components in low currents and to make sure that the chances for tangling or chafing are minimal.

The steady state currents impose a static load on all mooring components. Under static load the integrity of the mooring is based solely on the ultimate strength of the various mooring components. There are, however, other factors that must be taken into consideration when working in high wind and wave conditions.

Waves passing by the surface buoy can generate periodic increases in mooring tension. With a typical wave period of approximately seven seconds, millions of cycles can be

accumulated during a six month deployment. With this many tension cycles the fatigue strength of the various in-line components becomes a serious design consideration.

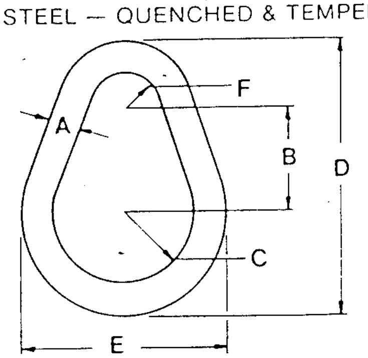
Little was known about the fatigue properties of standard components used in-line on a mooring prior to the 1989 pilot mooring for the Office of Naval Research (ONR) funded Marine Light in the Mixed Layer (MLML) experiment (Plueddemann *et al.*, 1995). The MLML pilot mooring was deployed in April 1989, approximately 300 miles south of Iceland in 2845 meters of water. Though the mooring was intended to remain on station for 5 months it failed after only 70 days. A 5/8 inch Crosby Laughlin weldless sling link with a rated working load of 4200 pounds and an ultimate breaking strength of six times the working load limit (WLL) was the component that failed (Figure 1). A high frequency tension data logger at the base of the MLML pilot mooring buoy bridle recorded tensions that ranged from less than 1000 to over 8500 pounds which was well under the ultimate breaking strength of the sling link. Tension records showed changes of up to 5000 pounds over less than four seconds.

To investigate this problem the manufacturer of the slings links, Crosby, agreed to perform a series of cyclic tests at their facility in Tulsa, Oklahoma, on the 5/8" sling links. Links were cycled between 2000 and 4000 pounds at 5 cycles per second. Inspections were made after 500,000, 1,000,000, and 2,000,000 cycles; however there were no obvious changes. The loading was changed to cycle between 420 and 6300 pounds, i.e., from a low load equal to 10% of the WLL to a high load equal to 1.5 times the WLL. Failure occurred after 52,800 cycles.

Further tests were conducted on additional new 5/8" links as well as 3/4" links and 5/8" anchor and chain shackles, and 3/4" anchor shackles. The results of those tests are in Table 1. Conclusions drawn from the testing and analysis of the failed component and similar components are that the link that failed on the MLML pilot mooring did so in fatigue. The origin of the crack was on the outside of the link, opposite the loaded area. No evidence of entrapped inclusions could be found. As indicated by concurrent testing at Crosby the fatigue limit had probably been exceeded and failure was only a matter of time under the loading conditions encountered during the life of this mooring. It was felt that an increase in link size from 5/8" to 3/4" would preclude further failure of this kind. In addition increasing the size of the shackle from 5/8" to 3/4" would also be a benefit. Since the 5/8" chain shackles faired better than the anchor shackles during the Crosby tests, it was also felt that wherever possible the chain style shackle should be used.

S-341 & G-341
WELDLESS SLING LINKS

FORGED STEEL — QUENCHED & TEMPERED



STOCK DIA. A	B	C	D	E	F	WEIGHT EACH	WORK LOAD* SINGLE PULL POUNDS
3/8	1.13	.75	3.00	2.25	.38	.23	1,800
1/2	1.50	1.00	4.00	3.00	.50	.53	2,900
5/8	1.875	1.25	5.00	3.75	63	1 1	4,200
3/4	2.25	1.50	6.00	4.50	.75	1.9	6,000
7/8	2.63	1 75	7 00	5.25	.88	2.9	8,300
1	3.00	2.00	8.00	6.00	1.00	4.3	10,800
1 1/4	4.00	2.50	10.25	7.50	1.25	8.5	16,750
1 3/8	4.13	2.75	11.00	8.25	1.38	11.3	20,500

*Minimum ultimate strength six times working load limit

Figure 1: Photograph and manufacturer specifications of the 5/8" weldless sling link that failed during the 1989 deployment of the Marine Light in the Mixed Layer experiment pilot mooring.

Table 1. Crosby cyclic fatigue test results.

Component	Sample No.	Cycles to failure
5/8" Weldless Sling Links Cycled from 420 to 6300 pounds		
	1	507,000
	2	151,910
	3	122,170
	4	464,000
	5	116,000
	6	207,000
	7	399,000
3/4" Weldless Sling Links Cycled from 420 to 6300 pounds		
	1	No failure after 5,000,000
	2	No failure after 6,700,000
	3	6,200,000 (at 4-5 million cycles sample loaded to 30,000 pounds)
5/8" Anchor Shackles Cycled from 420 to 6300 pounds		
	1	116,000
	2	145,000
	3	69,000
	4	155,000
	5	156,000
	6	132,000
5/8" Chain Shackle Cycled from 420 to 6300 pounds		
	1	468,000
	2	161,800
	3	152,000
	4	419,000
	5	689,000
	6	1,000,000 plus
3/4" Anchor Shackles Cycled from 420 to 6300 pounds		
		No failures at over 1,000,000 cycles

Section III: Arabian Sea Fatigue Tests

If the sling links and shackles were susceptible to fatigue failure how would the other in-line components perform? To address these concerns an independent series of cyclic fatigue tests were conducted by Teledyne Brown Engineering, formerly of Woburn, MA, and more recently of Marion, MA, beginning in September 1993. The scope of the fatigue testing was expanded to include the majority of all in-line mooring components. The components tested included shackles of various sizes, configurations, and manufacturers, wire rope, instrument cages, chain, and a variety of links.

The machine used for the cyclic fatigue tests was a 100,000 pound capacity MTS servo hydraulic load frame. Figure 2 shows a typical setup while testing a series of shackles and weldless sling links. With the use of a "wiffle tree" (Figure 3) four strings of components could be tested at one time. The wiffle tree is used to compensate for any length differences between strings and therefore evenly distributes the load among the strings being tested. All tests were conducted in a dry environment. The frequency of the applied cyclic load was between 3 and 5 Hz.

All tests consisted of a combination of components such as shackles and sling links connected in series. Each series of tests is described below. The name assigned to a particular test refers to the major component(s) under consideration even though several items were under test. A summary of the test results appears in Table 2. Appendix 1 contains the data collected from all the tests.

A. 5/8" Hardware Tests

The first series of tests were with new 5/8" Crosby anchor shackles and 5/8" Crosby weldless sling links. Four parallel strings made up of several shackle–weldless sling link–shackle (SLS) units were tested. The bow of the shackle was always dipped into the weldless sling link. Between any two SLS units there was a 3/4" steel plate with two holes to accept the shackle bolts of two adjacent SLS units. Two load ranges were specified. The first test cyclically loaded the components between 400 and 7200 pounds at a frequency of 3 Hz. A second test with a new set of 5/8" hardware was cycled between 400 and 6300 pounds also at a frequency of 3 Hz.

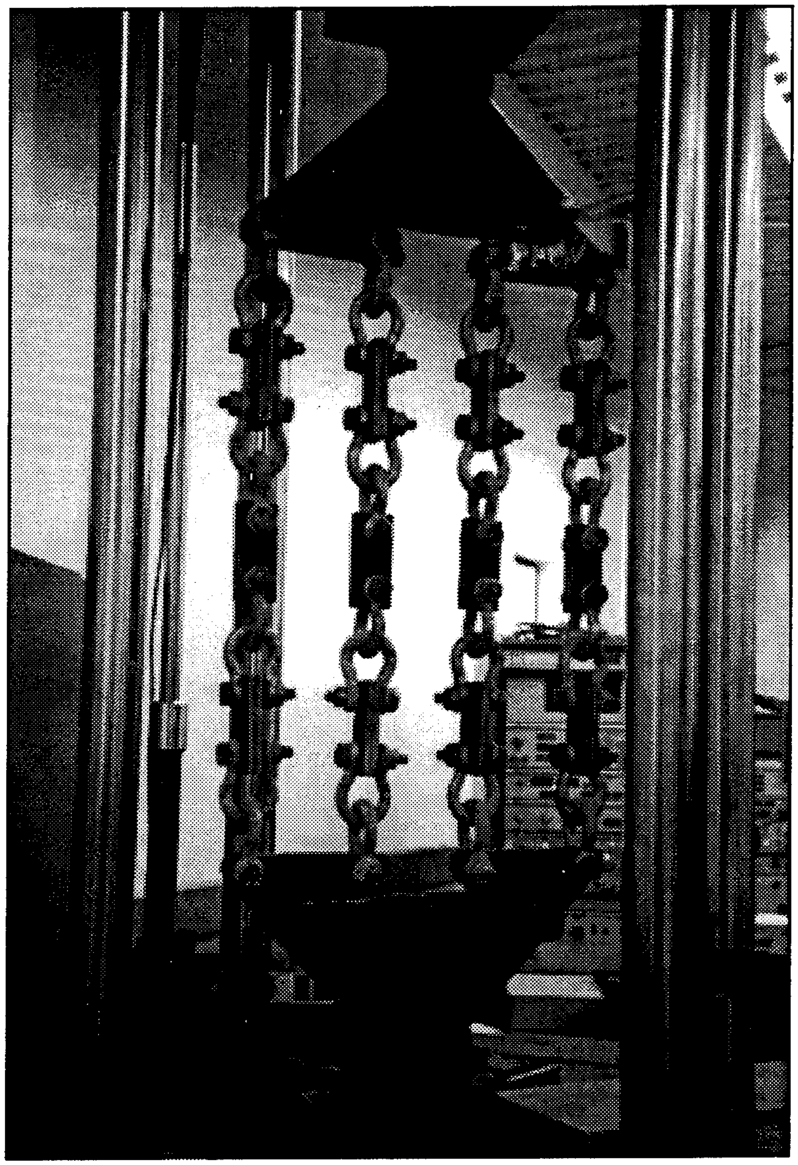


Figure 2: Photograph of the cyclic fatigue test setup while testing four strings of shackles.

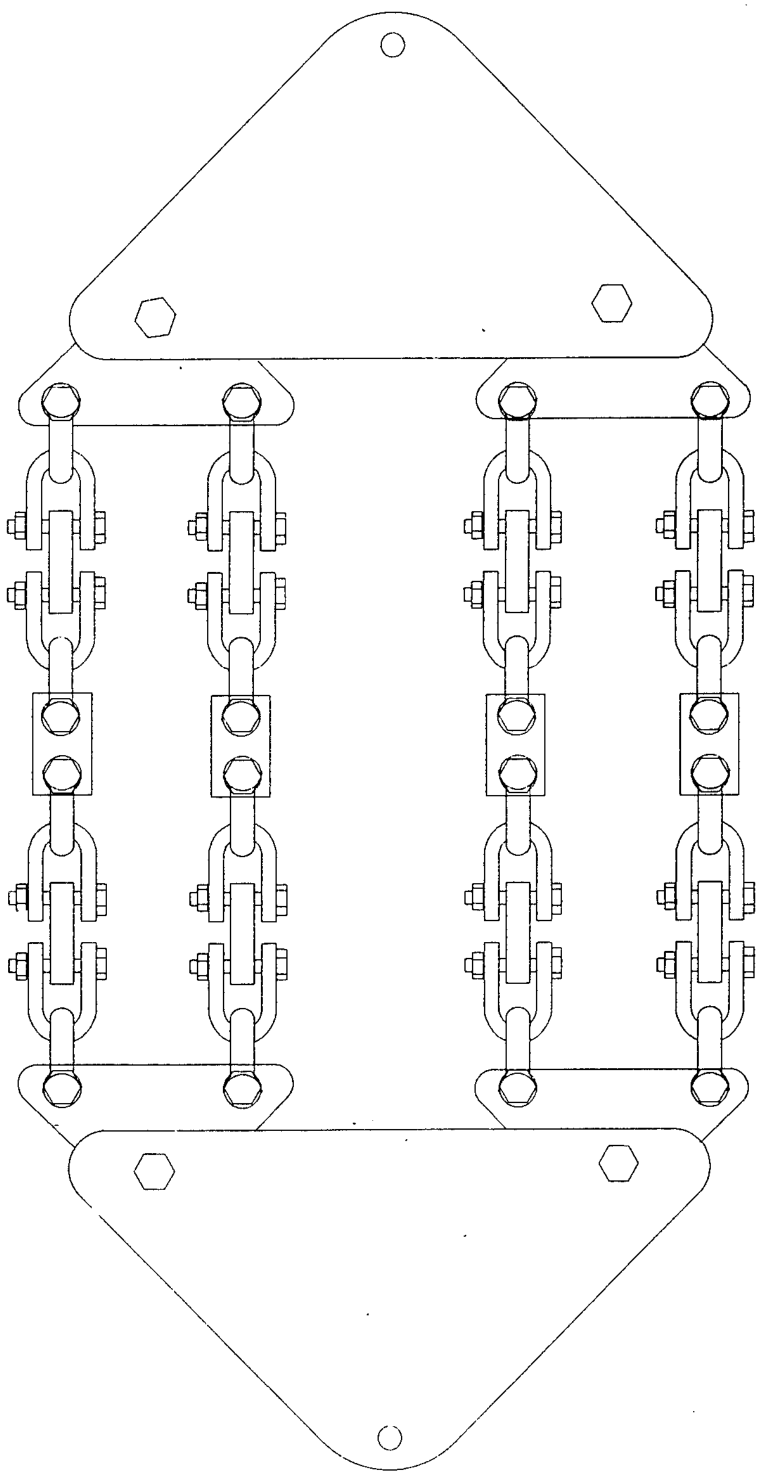


Figure 3: Schematic of the "wiffle tree" configuration used during the fatigue testing of multiple strings of hardware components. Shown here are four strings of shackles with WHOI fabricated steel plate interconnecting links.

Table 2. Summary of the WHOI cyclic fatigue test data.

Component	Anchor Shackles			Chain Shackles		Weldless Sling Links		Cages	Wire Rope	Chain	End Links
Component Size	5/8"	5/8"	3/4"	3/4"	3/4"	5/8"	3/4"	3/4"	7/16"	3/4"	7/8"
Surface Treatment	Galv.	Shot peened	Galv.	Shot peened	Galv.	Galv.	Galv.	Stainless	Galv.	Galv.	Galv.
Load Range											
400-6300 pounds											
Number of cycles to first failure	68,350					29,280					
Maximum number of cycles attained	582,680					126,400					
No. of Samples w/ cycle count > minimum	58					33					
Number of components that failed	34					30					
No. of components intact at max cycle count	9					0					
400-6800 pounds											
Number of cycles to first failure			351,240		263,670			351,240	198,850		
Maximum number of cycles attained			1,165,930		344,320			967,080	344,320		
No. of Samples w/ cycle count > minimum			13		7			2	4		
Number of components that failed			4		2			2	4		
No. of components intact at max cycle count			2		2			0	0		
400-7200 pounds											
Number of cycles to first failure	115,160					21,250					
Maximum number of cycles attained	522,820					46,550					
No. of Samples w/ cycle count > minimum	51					27					
Number of components that failed	35					17					
No. of components intact at max cycle count	8					0					
400-7500 pounds											
Number of cycles to first failure			117,390				66,800				
Maximum number of cycles attained			402,490				240,520				
No. of Samples w/ cycle count > minimum			24				20				
Number of components that failed			12				12				
No. of components intact at max cycle count			11				3				
400-8800 pounds											
Number of cycles to first failure			58,430				49,440				
Maximum number of cycles attained			170,090				128,700				
No. of Samples w/ cycle count > minimum			26				19				
Number of components that failed			13				12				
No. of components intact at max cycle count			11				1				
400-10200 pounds											
Number of cycles to first failure					61,290		10,090				
Maximum number of cycles attained					258,040		82,270				
No. of Samples w/ cycle count > minimum					26		44				
Number of components that failed					18		40				
No. of components intact at max cycle count					1		0				
2000-6000 pounds											
Number of cycles to first failure		555,210		5,000,000	911,320			*	995,470	*	*
Maximum number of cycles attained		5,000,000		14,000,000	5,000,000			5,000,000	2,594,840	5,000,000	14,000,000
No. of Samples w/ cycle count > minimum		6		8	12			2	4	4	8
Number of components that failed		3		1	5			0	2	0	0
No. of components intact at max cycle count		1		4	5			2	2	4	4
		* = did not break									

B. 3/4" Hardware Tests

The second series of tests were with new 3/4" Crosby chain shackles and weldless sling links. As with the earlier test each of the four parallel strings had several SLS units which were interconnected with the 3/4" steel plates. Three load ranges were selected for these tests. New hardware was used when the load ranges were changed. The first set of hardware were cycled between 400 and 10,200 pounds. A second test cycled a new set of hardware between 400 and 8800 pounds and a third load range used was between 400 and 7500 pounds.

C. Cage Tests (First Series)

The next fatigue test conducted had two short versions of the Vector Measuring Current Meter (VMCM) cage with 3/4" cage rods in line with 3/4" anchor shackles to hold the cages in the testing machine. The VMCM instrument cage goes in-line on a mooring just like a shackle or link and is therefore susceptible to fatigue failure. Since the test machine could not accommodate a full length cage (71 inches) a short version, 48 inches in length, was fabricated by Stonebridge Corp of Holliston, MA. Stonebridge was the same fabricator that had made all of the Upper Ocean Processes Group's previous VMCM cages. The cages were initially tested in parallel with two back to back shackles above and below each cage. The cages were cycled between 400 and 6800 pounds until failure. After the first cage failed the second cage was tested as a single string. Unbroken shackles from the first cage were used to replace hardware that broke during the testing of the second cage. Testing continued until both cages had failed.

D. Cage Tests (Second Series)

A second series of cage tests were conducted on two newly fabricated short versions of the VMCM instrument cage. Early cage failure during the previous cage tests were attributed to poorly defined fabrication specifications. Two cages fabricated to new specifications were donated by Stonebridge Corporation. The new test cages were slightly shorter (37" versus 48") than the pair tested earlier. Above and below each cage there was a shot peened 3/4" Crosby chain shackle, a 7/8" Crosby weldless end link, and a shot peened 5/8" Crosby anchor shackle. The shot peened 3/4" chain shackle and the 7/8" weldless end link were previously tested to 5 million cycles during the chain test. The shot peened 5/8" shackles were new. All hardware was cycled between 2000-6000 pounds. The test was terminated after five million cycles.

E. Wire Rope Tests (First Series)

Four 7/16" diameter, polyethylene jacketed, torque balanced, 3 x 19 wire rope samples each 42" long with swaged fittings at both ends were tested. The MacWhyte wire rope

samples were swaged using National closed swage fittings by the WHOI rigging shop. The four samples were tested in parallel until the first failure occurred. Two samples were then tested in parallel until only one sample was left which was then tested as a single string. Two back to back 3/4" shackles were placed above and below each wire rope sample. Five of the shackles used with the wire rope were anchor shackles from the cage tests previously conducted. The remainder were new chain shackles. The wire rope was cycled between 400 and 6800 pounds. Testing was terminated when all four wire samples were broken.

F. Wire Rope Tests (Second Series)

Early failure of the first wire samples prompted a second series of tests on four new shots of 7/16" diameter wire rope that was also swaged by the WHOI rigging shop. It was suspected that proper swaging techniques had not been followed for the first samples. The test setup was similar to the first series of wire tests except that new Crosby 3/4" chain type shackles were used back to back above and below the wire samples. The wire rope was cycled between 2000 and 6000 pounds. After the second wire failure the test was terminated.

G. Chain tests

Four strings of Campbell 3/4" system 3 proof coil chain were tested in parallel. The chain samples were each 36" in length and had a shot peened 3/4" Crosby chain shackle, a 7/8" Crosby weldless end link and a 3/4" Crosby chain shackle above and below it. All hardware was cycled between 2000 and 6000 pounds. The test was terminated after reaching five million cycles.

H. Shot Peened Hardware

Bigger is not always better. Increasing the size of mooring hardware drives up the cost and further restricts the carrying capacity of the mooring. It can also require instrument redesign if the load carrying member cannot accommodate the larger hardware. In an effort to improve the fatigue life of various hardware components without increasing their size, several test samples were shot peened prior to fatigue testing. Shot peening is a process whereby a component is blasted with small spherical media called shot in a manner similar to the process of sand blasting. It differs from sand blasting in that the media used in shot peening is more rounded rather than angular and sharp as in sand blasting. Each piece of shot acts like a small ball peen hammer and tends to dimple the surface that it strikes. At each dimple site the surface fiber of the material is placed in tension. Immediately below the surface of each dimple the material is highly stressed in compression so as to counteract the tensile stress at the surface. A shot peened part with its many overlapping dimples therefore has a surface layer with residual

compressive stress. Cracks do not tend to initiate or propagate in a compressive stress zone. Since cracks usually start at the surface, a shot peened component will take longer to develop a crack thereby increasing the fatigue life of the part. Many materials will also increase in surface hardness due to the cold working effect of shot peening.

The compressive stresses introduced by shot peening increase the resistance to fatigue failures, corrosion fatigue, stress corrosion cracking, hydrogen assisted cracking, fretting, galling, and erosion caused by cavitation. The benefits of cold working include work hardening, and intergranular corrosion resistance.

Samples of 3/4" Crosby chain shackles and 5/8" anchor shackles were shot peened by Metal Improvement Company, Inc. of Windsor, Connecticut, at their Lynn, Massachusetts, plant. The shot size used was MI-330, the intensity was .012 to .016A with 100% coverage per Mil Spec 13165C, Section 6.11, method b.

I. Load Range Selection

During the fatigue tests the components are repeatedly cycled from a minimum tensile load to a maximum load at about 3 Hz. The loads selected for these cyclic tests were initially based on those specified for the first series of tests conducted by Crosby following the MLML 89 pilot mooring failure. The component in question at that time was a 5/8" weldless sling link which has a working load limit of 4200 pounds. The minimum load was 10% of the working load limit and the maximum load was 1.5 times the working load limit or 400 to 6300 pounds. Since the original Crosby tests had used that range we wanted to duplicate those tests to see how repeatable the results were. The first tests conducted were therefore on 5/8" hardware using the 400 to 6300 pound range.

It was our desire to develop an S/N curve for the various hardware components. The S/N curve shows the relationship between stress amplitude (S) and the number of cycles to failure (N). Several tests were conducted at different load ranges to see what affect it would have on the number of cycles to failure. (Load range is defined here as the maximum tension minus the minimum tension attained for each loading cycle. For example, a sample cycled between 2000 and 6000 pounds has a load range of 4000 pounds.) We hypothesized that cyclic loads between 400 and 7200 pounds would decrease the number of cycles to failure by an order of magnitude. In addition, a cyclic test between 400 and 5300 pounds was planned in order to obtain an order of magnitude increase in the number of cycles to failure. Although

the 400 to 5300 pound cyclic test was never actually conducted the range was utilized in planning the loads for larger hardware sizes.

The 5/8" hardware fatigue results from the 400 to 6300 and 400 to 7200 tests indicated that the 5/8" hardware would not be appropriate for those sections of the mooring where large dynamic tensions could be found. Rather than continue testing the 5/8" hardware, tests were started on the 3/4" size hardware. The loads chosen for the 3/4" hardware were the result of increasing the maximum tension used for the 5/8" hardware by a factor of 1.4 which is proportional to the cross sectional areas of the two hardware sizes.

The first series of cage and wire rope tests were conducted using cyclic loads from 400 to 6800 pounds. This range was chosen because it encompassed 99% of the tensions seen by the MLML mooring (M. Grosenbaugh, personal communication). Following the first series of cage and wire rope tests the tensions were changed to cycle between 2000 to 6000 pounds. The tests cycling between 400 and 6800 pounds were thought to be an extreme condition and it was unlikely that every tension cycle experienced by the mooring would be over that full range. The more realistic 2000 to 6000 pound tests represent a static load of 4000 pounds tension from the weight of the mooring components and the drag from a steady state design current coupled with a +/- 2000 pound dynamic tension from the surface wave conditions.

Section IV: Results

The following figures (Figures 4a to 4u) show for a particular size, type and load range the percentage of samples intact with increasing number of cycles. All like components (size and type) tested with the same load ranges are grouped together. For example the 3/4" anchor shackles tested between 400 and 6800 pounds are separate from the 3/4" chain shackles tested over the same range. The data used to generate these figures include all component failures plus those components that attained the maximum number of cycles and remained intact. Some variation in scales was necessary to adequately show the details. All weldless sling links are plotted to the same scale. The scales used in plotting the data for all the 5/8" and 3/4" hardware with the exception of the sling links mentioned above and tests cycled between 2000 and 6000 pounds are the same. Test results from the cages, wire rope, chain, weldless endlinks, and 5/8" and 3/4" hardware tested between 2000 and 6000 pounds have also been plotted with the same scale for comparison purposes. The weldless sling link data were grouped in bins of 5000 cycles while all other data were grouped in bins of 10000 cycles.

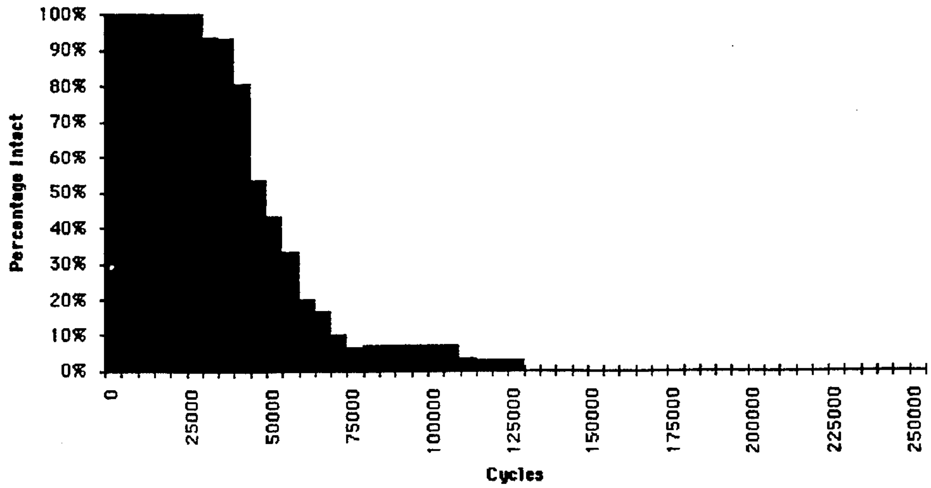


Figure 4a. 5/8" Weldless Sling Links cycled between 400 and 6300 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 30 and the test was terminated at 126,400 cycles with no intact samples remaining.

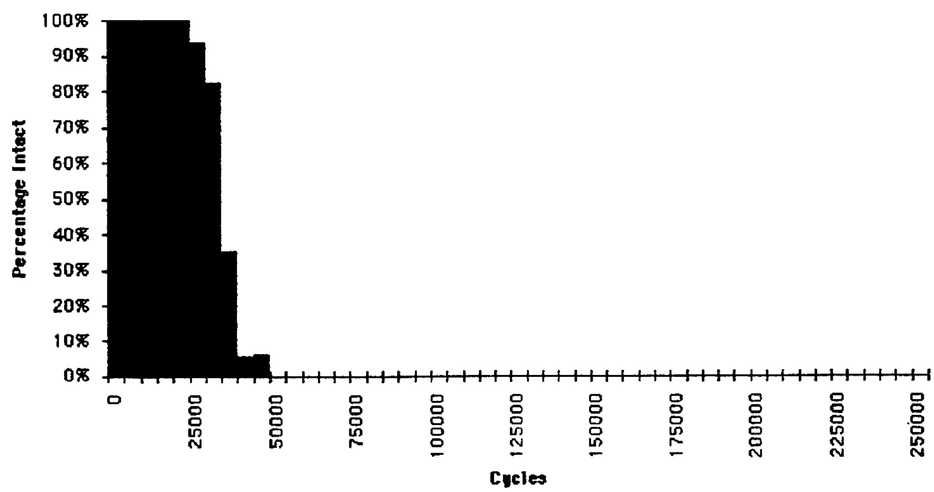


Figure 4b. 5/8" Weldless Sling Links cycled between 400 and 7200 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 17 and the test was terminated at 46,550 cycles with no intact samples remaining.

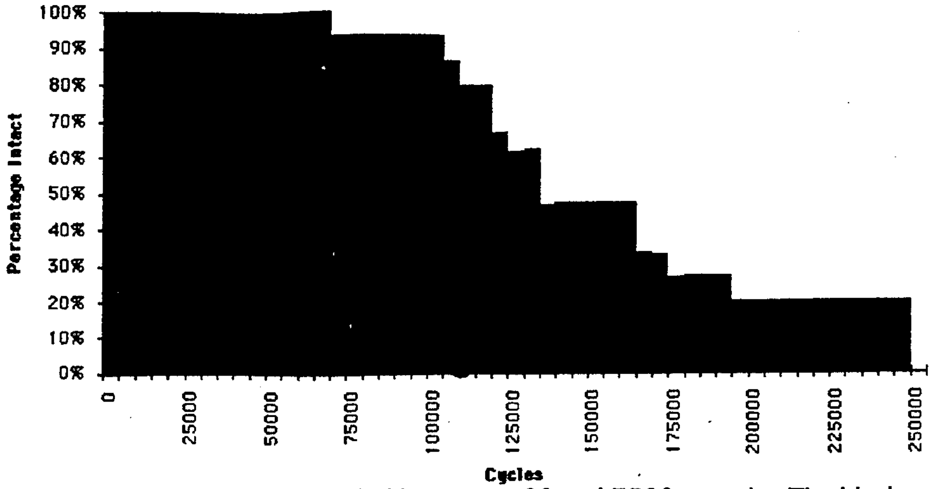


Figure 4c. 3/4" Weldless Sling Links cycled between 400 and 7500 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 15 and the test was terminated at 240,520 cycles with three intact samples remaining.

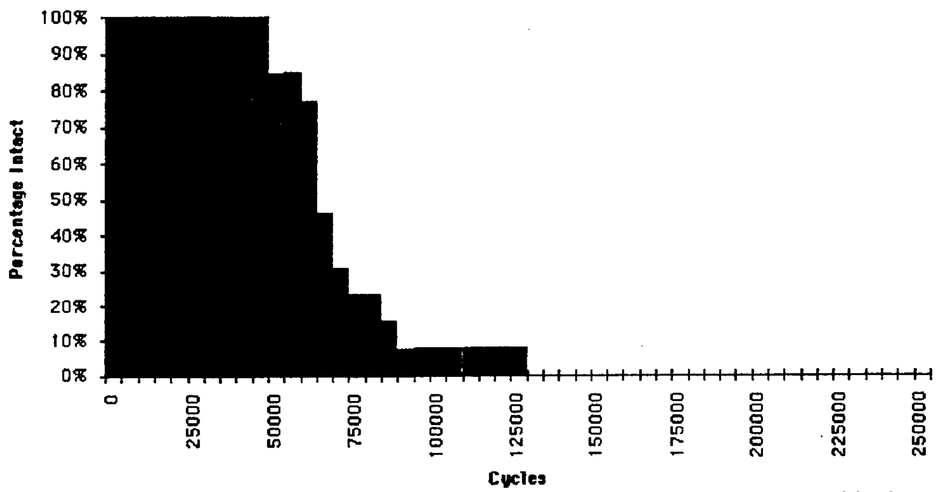


Figure 4d. 3/4" Weldless Sling Links cycled between 400 and 8800 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 13 and the test was terminated at 128,700 cycles with one intact sample remaining.

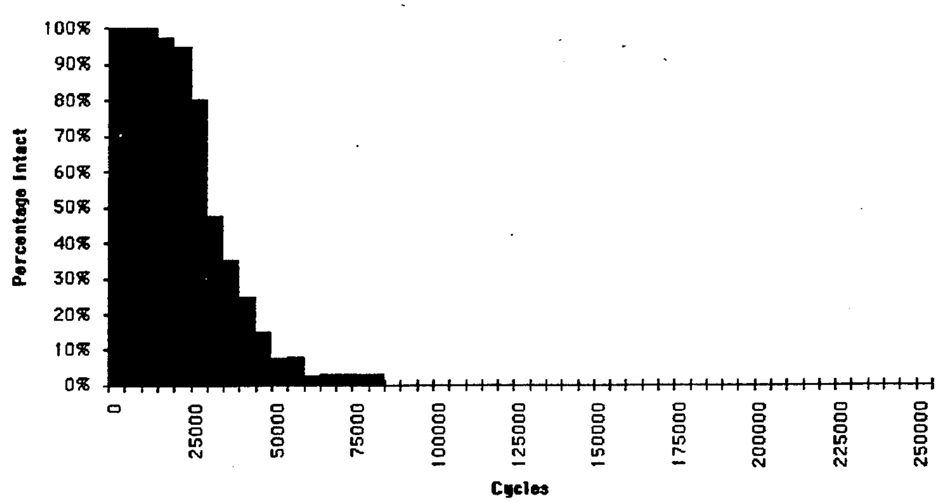


Figure 4e. 3/4" Weldless Sling Links cycled between 400 and 10,200 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 40 and the test was terminated at 82,270 cycles with no intact samples remaining.

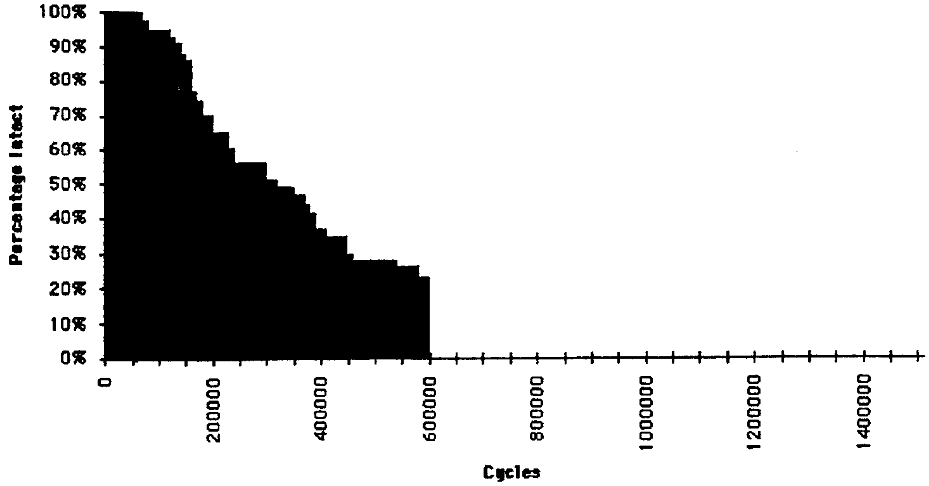


Figure 4f. 5/8" Anchor Shackles cycled between 400 and 6300 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 43 and the test was terminated at 582,680 cycles with ten intact samples remaining.

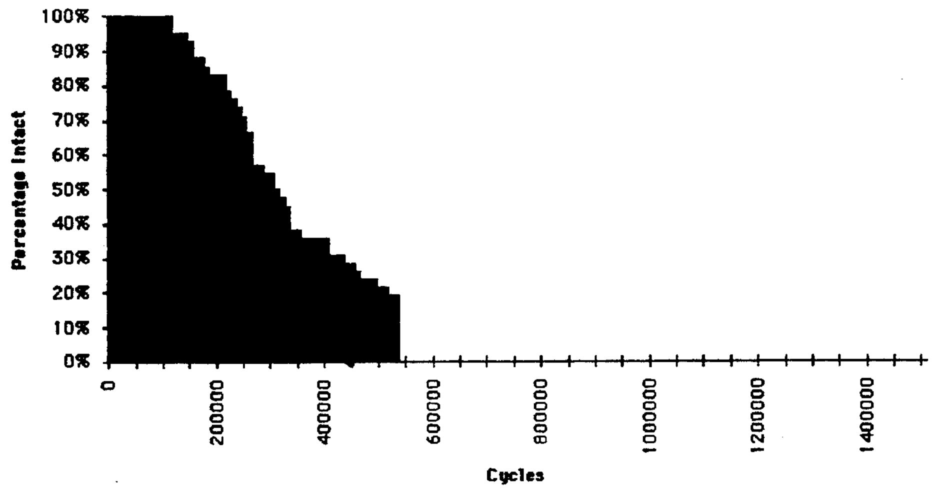


Figure 4g. 5/8" Anchor Shackles cycled between 400 and 7200 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 42 and the test was terminated at 522,820 cycles with eight intact samples remaining.

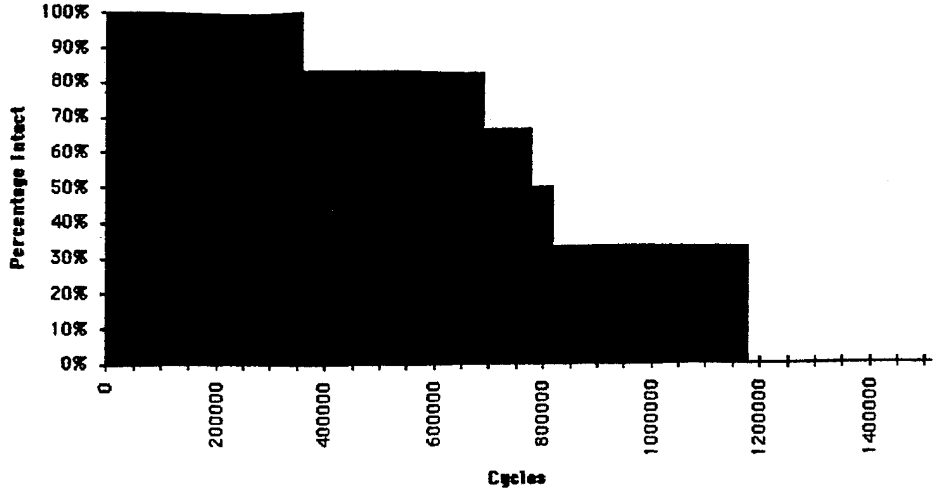


Figure 4h. 3/4" Anchor Shackles cycled between 400 and 6800 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 6 and the test was terminated at 1,165,930 cycles with two intact samples remaining.

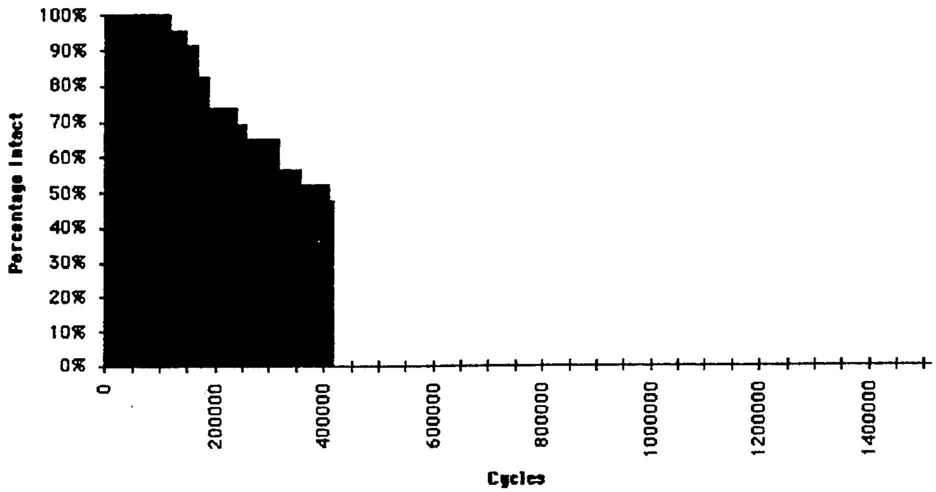


Figure 4i. 3/4" Anchor shackles cycled between 400 and 7500 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 23 and the test was terminated at 402,490 cycles with eleven intact samples remaining.

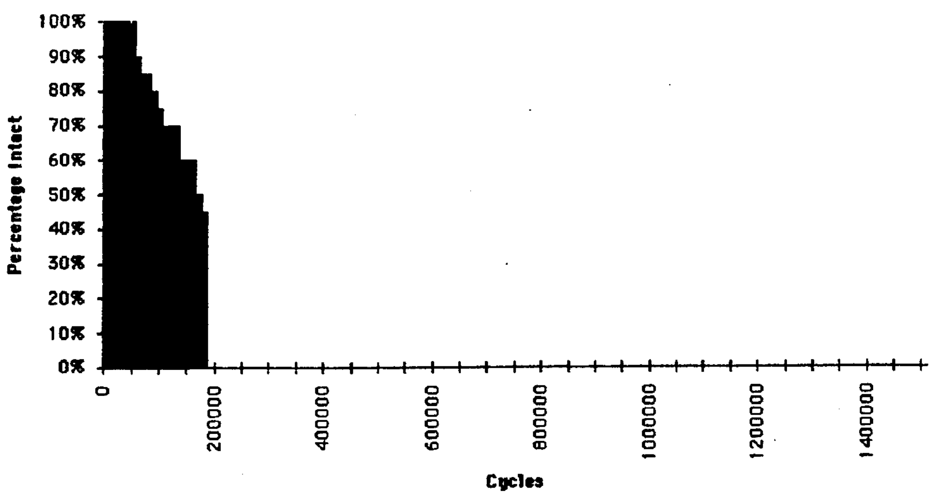


Figure 4j. 3/4" Anchor Shackles cycled between 400 and 8800 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 20 and the test was terminated at 170,090 cycles with eight intact samples remaining.

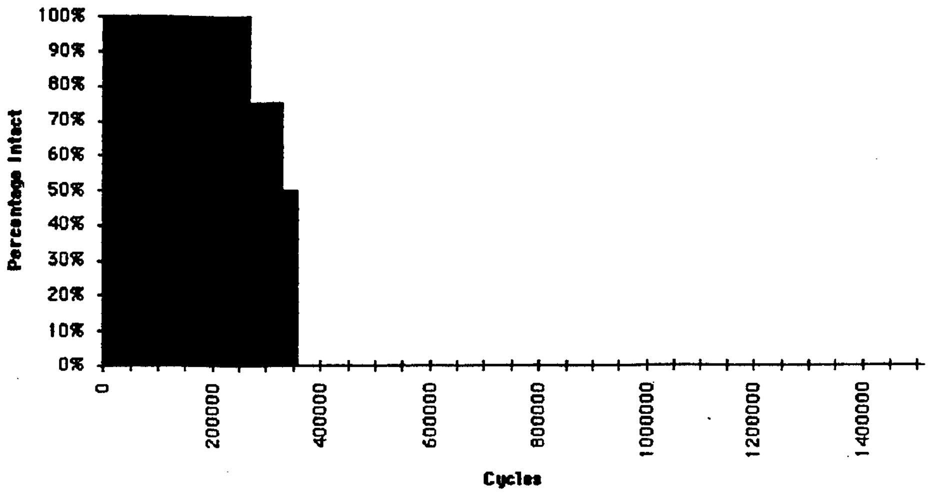


Figure 4k. 3/4" Chain Shackles cycled between 400 and 6800 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 4 and the test was terminated at 344,320 cycles with two intact samples remaining.

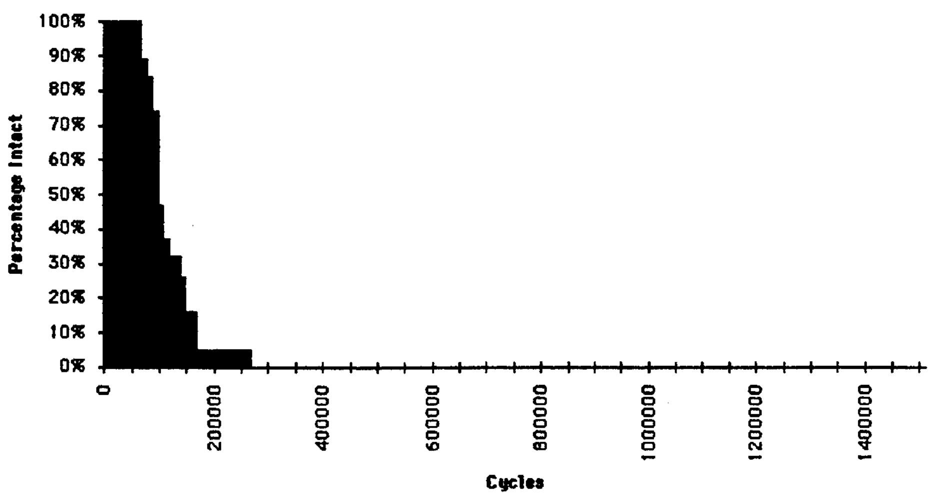


Figure 4l. 3/4" Chain Shackles cycled between 400 and 10,200 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 19 and the test was terminated at 258,040 cycles with one intact sample remaining.

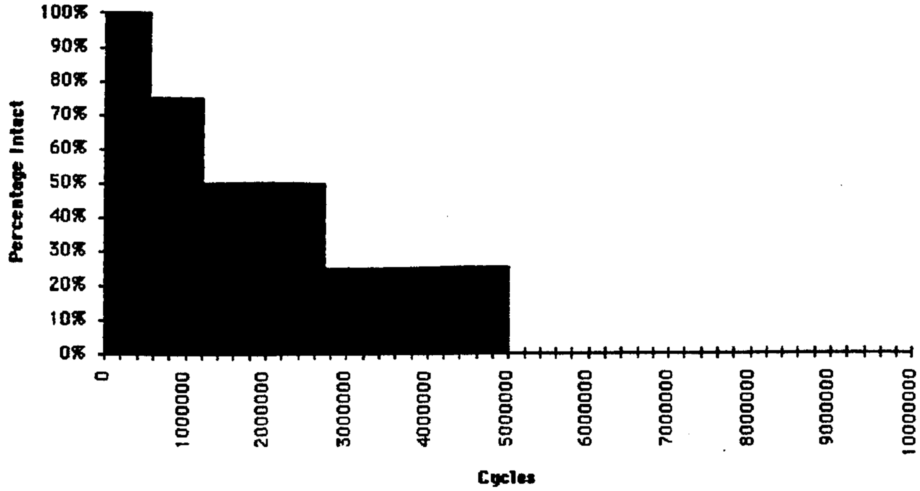


Figure 4m. 5/8" Shot Peened Anchor Shackles cycled between 2000 and 6000 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 4 and the test was terminated at 5,000,000 cycles with one intact sample remaining.

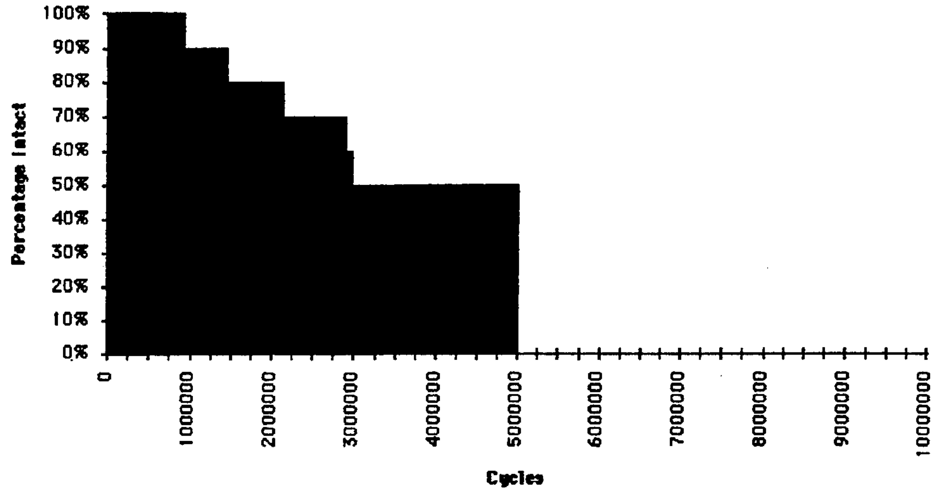


Figure 4n. 3/4" Chain Shackles cycled between 2000 and 6000 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 10 and the test was terminated at 5,000,000 cycles with five intact samples remaining.

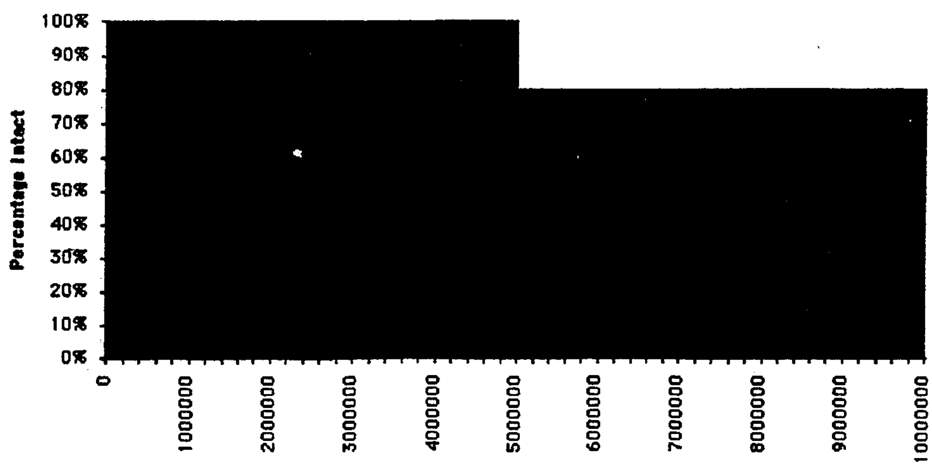


Figure 4o. 3/4" Shot Peened Chain Shackles cycled between 2000 and 6000 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 5 and the test was terminated at 10,000,000 cycles with four intact samples remaining.

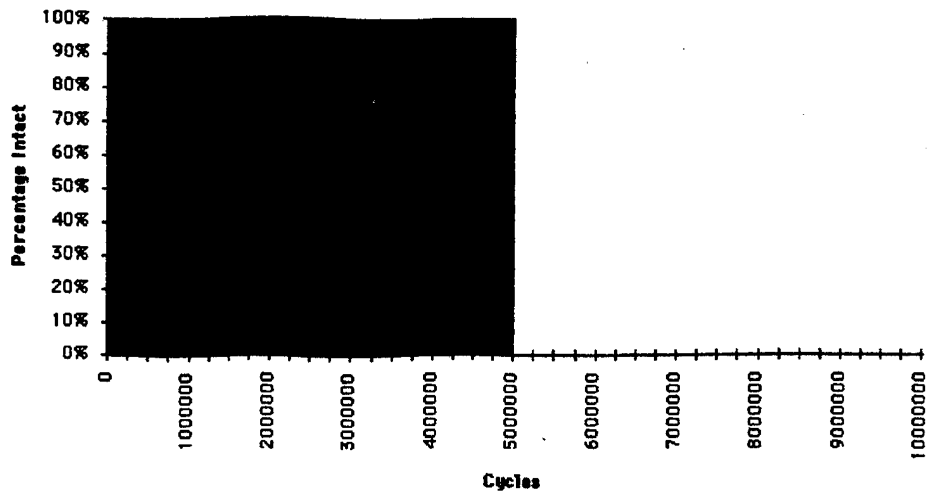


Figure 4p. 3/4" Chain cycled between 2000 and 6000 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 4 and the test was terminated at 5,000,000 cycles with four intact samples remaining.

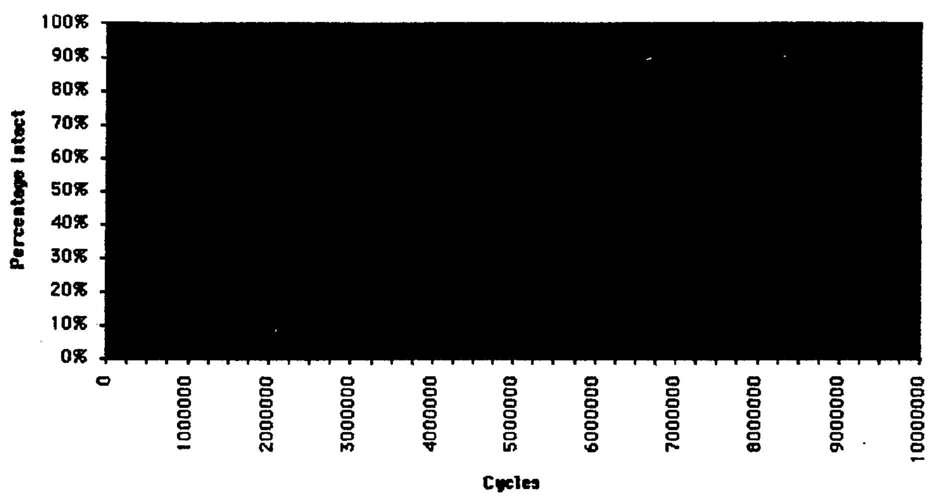


Figure 4q. 7/8" Weldless End Links cycled between 2000 and 6000 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 4 and the test was terminated at 10,000,000 cycles with four intact samples remaining.

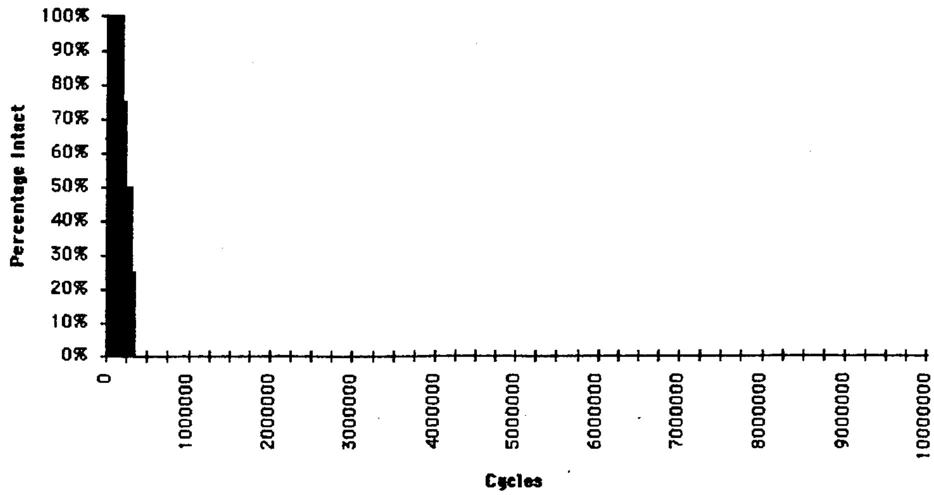


Figure 4r. 7/16" Torque Balanced Wire Rope cycled between 400 and 6800 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 4 and the test was terminated at 344,320 cycles with no intact samples remaining.

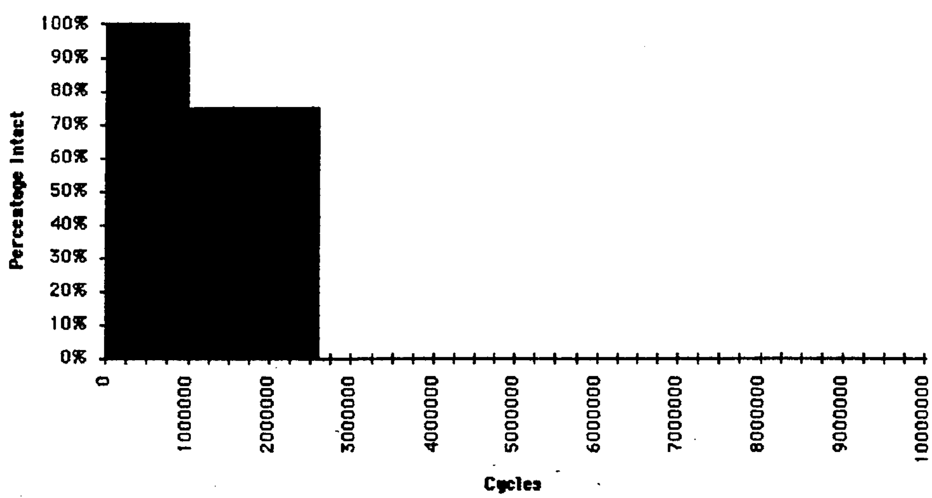


Figure 4s. 7/16" Torque Balanced Wire Rope cycled between 2000 and 6000 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 4 and the test was terminated at 2,594,840 cycles with two intact samples remaining.

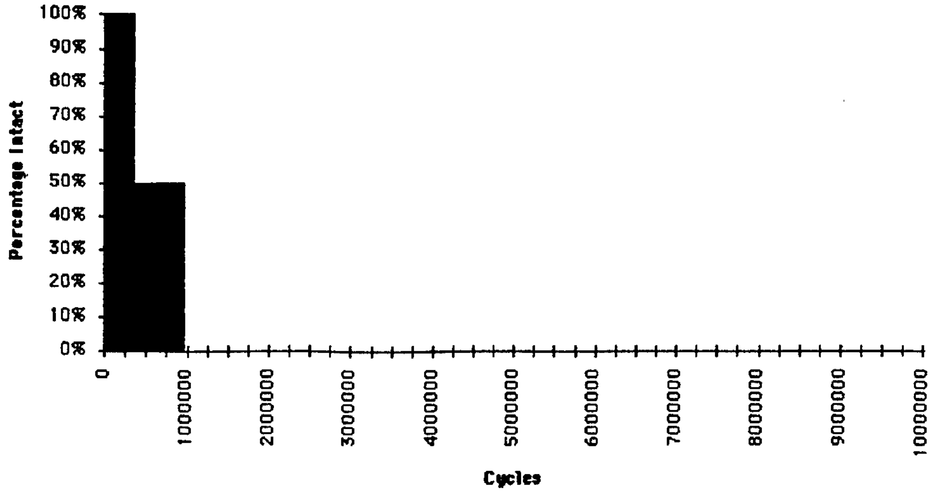


Figure 4t. VMCM-like cage with shortened 3/4" cage rods cycled between 400 and 6800 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 2 and the test was terminated at 967,080 cycles with no intact samples remaining.

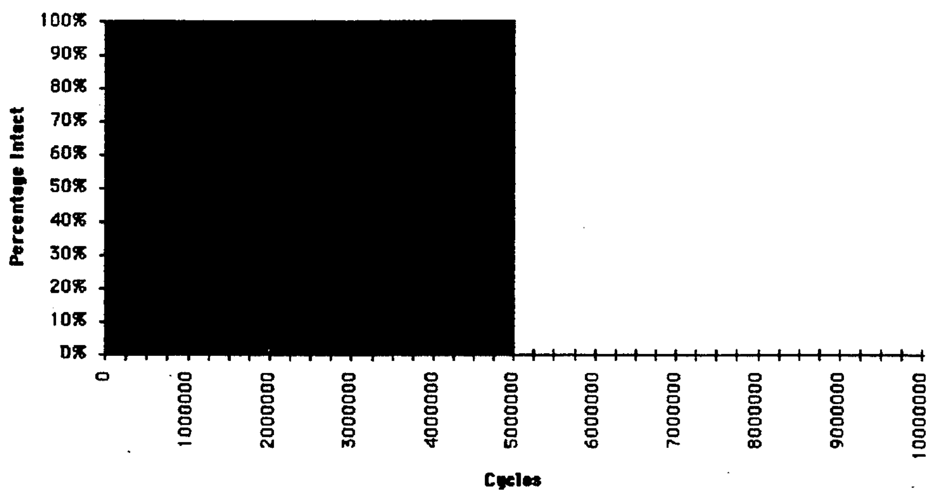


Figure 4u. VMCM-like cage with shortened 3/4" cage rods cycled between 2000 and 6000 pounds. The blackened section depicts the percentage of samples intact at the cycles indicated. The sample size was 2 and the test was terminated at 5,000,000 cycles with two intact samples remaining.

A. Weldless Links and Shackles

Due to the expense of conducting the fatigue tests it was difficult to obtain a complete data set whereby all components are tested for all ranges. Figure 5 shows for 5/8" and 3/4" weldless sling links and 3/4" chain and anchor shackles a plot of cycles to first failure as a function of load range. The combined plot clearly shows the trend that as the load range increases the number of cycles to first failure decreases. A relatively small increase in load range can significantly reduce the number of cycles the component can endure. Take, for example, the 3/4" anchor shackle. By increasing the load range from 6400 pounds to 8400 pounds or an increase of 31%, the number of cycles to first failure dropped from 351,000 to 58,000 or by 83%. Hence, moderate increases in the loading on a mooring can greatly shorten its life expectancy.

The component that failed due to fatigue most often with the fewest number of cycles was the weldless sling link, more commonly known as a pear ring. The weldless sling link was the same component that had failed on the MLML 1989 pilot mooring. The shape of the component is such that the failure always occurs at the end with the large radius of curvature.

The purpose of the weldless sling link in a mooring is to provide places along the mooring where it can be "stopped off" for a variety of reasons such as to insert or remove an instrument, a shot of wire, or as a safe point from which to tow the mooring. A link is usually found between any two adjacent shackles. During deployment and recovery operations an eye hook or similar device on the end of a deck line is snapped into the ring and the line is then secured to a cleat.

The 5/8" weldless sling links failed as early as 21,250 cycles when loaded between 400 and 7200 pounds. This is equivalent to 1.7 days assuming the waves creating such loads have a 7 second period. The 3/4" weldless sling link did not have a much better showing. In comparing hardware of the same size that was tested at the same load ranges the weldless sling link always failed after fewer cycles.

Since the weldless sling links did not fare well in general, a substitute component was sought. The replacement component had to offer the same capability as the weldless sling link but had to have a greater fatigue life. The 7/8" weldless end link met the necessary size requirements and performed well during the fatigue tests. The 7/8" weldless end links were loaded between 2000 and 6000 pounds and had not experienced a failure after 14 million

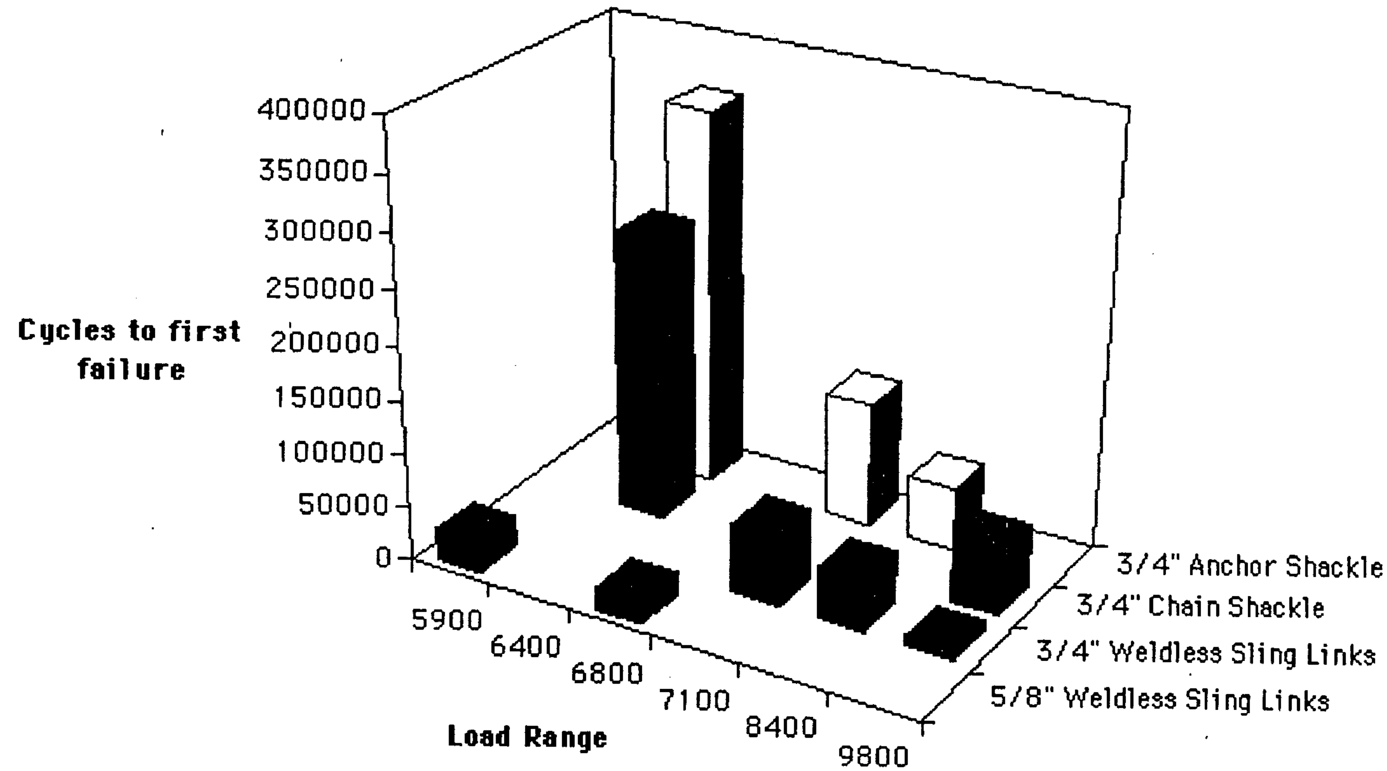


Figure 5. Three dimensional representation of the number of cycles to first failure as a function of load range for two types of shackles and two sizes of weldless sling links.

cycles. A smaller size end link would probably have been adequate from a fatigue stand point but the 7/8" size was chosen in order to have a large enough opening to accommodate a hook for the purposes mentioned above. The necessary over-sizing contributed to the improved fatigue life but not without a weight penalty. Four 7/8" weldless sling links survived 4 million load cycles from 2000 to 6000 pounds. Due to the lack of funds these components could not be tested to the extent of the 7/8" weldless end links. The end links however were the preferred component because they weighed slightly less than the sling links.

S/N Diagram for Weldless Sling Links and Shackles

Fatigue data are often presented in the form of S/N curves where the cyclic stress amplitude is plotted versus the number of cycles to failure. An S/N curve was generated from the data obtained during the fatigue tests of weldless sling links and safety shackles. Since the failure of any single component in line on a mooring is catastrophic we have taken a conservative approach here and used the number of cycles to the first failure. Seven different load ranges were used in the fatigue tests. The means of the load ranges were all very close to 4000 pounds. To account for the small differences in the mean loads, an adjustment was made to the actual test amplitude (y) using:

$$y^* = y(Yu - 4000)/(Yu - Tm) \quad (1)$$

where y^* is the effective amplitude, Tm is the mean tension, and Yu is the ultimate strength of the given component (Grosenbaugh, 1995). The effective amplitude for a particular test was normalized using the ultimate strength of the component being tested. Figure 6 shows an S/N diagram for both weldless sling links and safety shackles.

Using the test data shown in Figure 6 along with the expression:

$$N = (y/T)^q \quad (2)$$

which assumes that the number of cycles to failure (N) is related to the amplitude of the dynamic tension (T), we have determined the values of y and q for both types of components. The parameters of q and y are fatigue constants related to the material and geometry of the given mooring component. Sling links can be represented using $y=1.8Yu$, and $q=3.8$ and safety shackles by $y=1.5Yu$ and $q=3.8$ where Yu is the ultimate strength of the given component (Grosenbaugh, 1995).

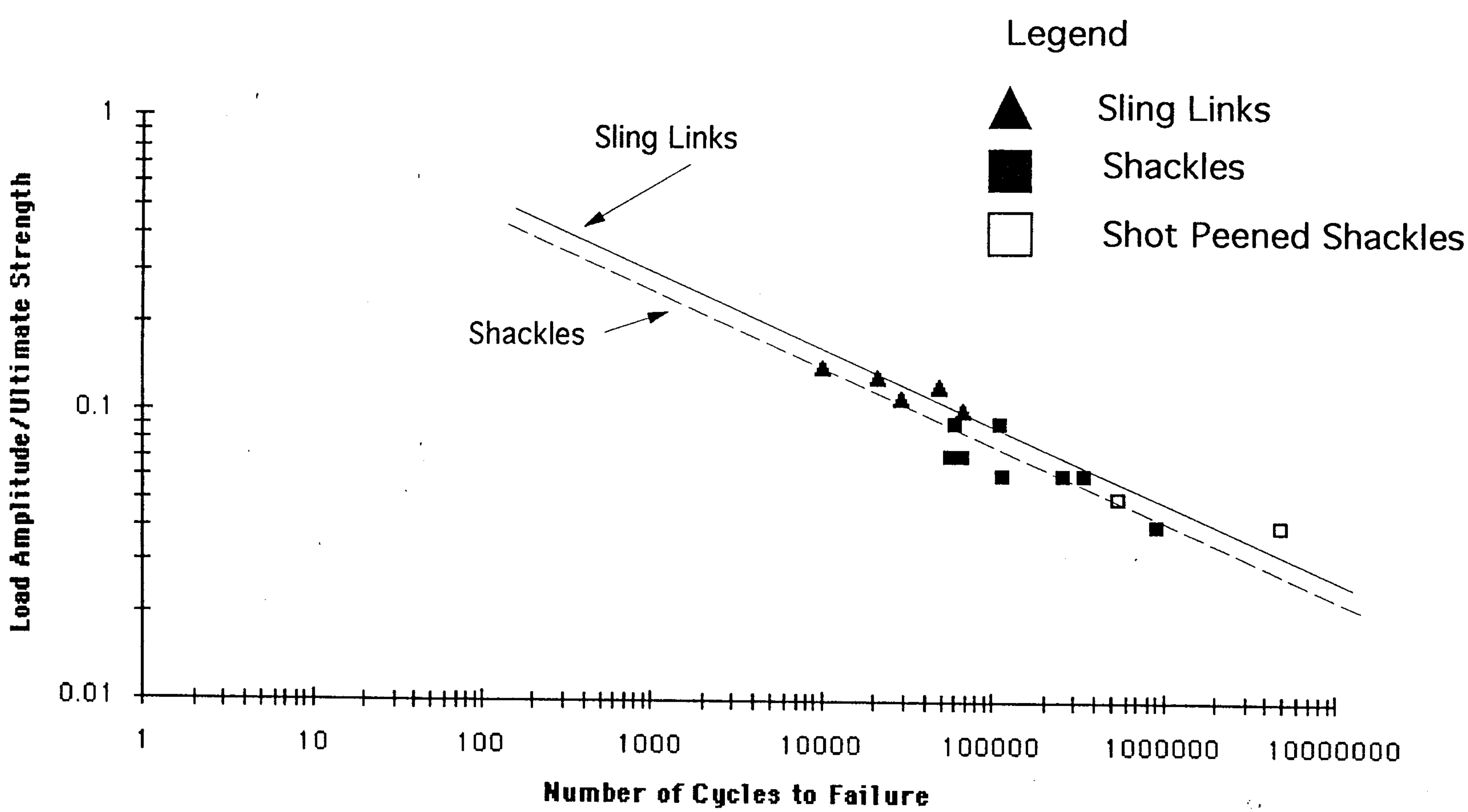


Figure 6. S/N diagram for shackles and sling links

B. Shot Peened Shackles

Due to the sparse availability of environmental data at a particular mooring site it is not always easy to predict the loading a mooring will experience. To compensate for the unknowns there is a tendency to increase the size of the hardware thereby increasing its load carrying capability. There is, however, a penalty that must be considered. Larger hardware usually weighs more and tends to be more costly. The increase in weight in turn reduces the payload that a mooring can carry. Bale sizes on existing instrumentation also places certain limitations on the size hardware that can be used. Specifying larger hardware can require retrofitting existing equipment with larger bails or possibly require new fabrication of load cages and strength members.

Shot peening is one technique that has been shown to improve the fatigue life of some components without physically increasing their size. During the Arabian Sea fatigue tests the fatigue life of standard galvanized 3/4" chain shackles were compared with shot peened 3/4" non-galvanized shackles.

Thirteen galvanized 3/4" Crosby chain shackles were cycled between 2000 and 6000 pounds. The first failure occurred after 911,320 cycles. One of the thirteen shackles tested was a replacement for a failed component and was still intact when the test was terminated after only accumulating 570,490 cycles. Since it had not failed and did not reach the minimum number of cycles to the first failure we have disregarded it here. Of the remaining 12 shackles five or 42% failed between 911,320 and 2,972,720 cycles. The same percentage were intact after 5,000,000 cycles.

In comparison, eight 3/4" Crosby chain shackles were shot peened and cycled between 2000 and 6000 pounds. The first and only failure occurred after 5,000,000 cycles. Six of the remaining 7 shackles were further tested and all reached 7,727,410 cycles without any failures. Of those six, four were randomly selected and cycled to 14,000,000 cycles without any failures. Based on these results, the shot peening process seemed to greatly improve the fatigue life of the 3/4" shackles tested.

A drawback of the shot peening process is that the component should not be galvanized after shot peening. Temperature associated with hot dip galvanizing will stress relieve the component and negate the effects of the shot peening. An alternate means of corrosion protection is therefore needed. A baked-on coating called Xylan is one technique presently

under test. The application temperature is less than that used during galvanizing and will not affect the shot peening.

C. Cages

During the first series of cage testing it became obvious that fabrication specifications are a critical component of repeatable performance. In testing a sample, one hopes that it is representative of the whole. If there is no standard to adhere to then the variability from part to part makes sample test results meaningless. Poorly defined welding techniques, inadequate quality control and testing, and uncertainty about the raw materials used can lead to problems.

Two test cages were fabricated by Stonebridge Corp. using the same drawings previously used to fabricate a number of other VMCM cages. These cages were initially tested from 400 to 6800 pounds and the first failure occurred after just 351,240 cycles. The early failure was attributed to a fabrication technique that was not appropriate for the type of service expected of these cages. Having identified the problem it became clear that the cage fabrication specifications had to be spelled out more clearly. With the help of Stonebridge Corp. the appropriate welding specifications were identified. In addition dye penetrant inspection of all welds was required by a certified inspector and certification of the origin of the material was also required. The specifications adopted for cage fabrication are as follows:

- All cages are to be welded per MIL-STD-2219 Class C. Certification is required.
- All welds are to undergo liquid penetrant inspection per MIL-STD-6866. Certification is required.
- The type 316 stainless steel must conform to MIL Spec number QQ-S-763 for bar stock and MIL Spec number QQ-S-766 or ASTM-A-240 for sheet or plate. Material certification is required.
- All rod stock must be a continuous piece.
- Finished products should be stamped with the welder's certification number and the designation for liquid penetrant inspection.
- Parts will not be accepted for use on moorings without the above mentioned certifications.

There is, of course, a cost associated with this extra effort; however, it is relatively small when weighed against the total cost of the mooring or the cost of recovering a failed mooring.

Stonebridge also provided assistance in designing a gusset to be welded between the longitudinal members and the end bales to stiffen the cage and improve its fatigue life. Since new cage fabrication was not possible due to financial restraints the gussets were a Band-Aid approach to improve their performance.

Two new test cages were fabricated using all the new specifications and the gussets. These cages were tested between 2000 and 6000 pounds. After 5 million cycles neither cage had failed and the test was terminated. Since the second set of test cages had performed so well, ten existing cages (enough for two Arabian Sea deployments) were retrofitted with gussets and all welds were brought up to the new specification and inspected.

D. Chain

Four samples of 3/4" diameter Campbell System 3 proof coil chain were cycled between 2000 and 6000 pounds for a total of 5 million cycles without any failures. Based on these results the System 3 chain was specified for the Arabian Sea surface mooring.

E. Wire Rope

Two series of wire rope tests were conducted. The number of cycles to failure for the first series of tests cycled between 400 and 6800 pounds seemed surprisingly low. Examination of the failures indicated that the wire had not been properly swaged since the breaks had occurred inside the swage socket. It was attributed to an incorrect filler wire size and to an improper technique used by the operator to work the swage onto the wire. During the second series of wire tests which cycled the wire between 2000 and 6000 pounds the test was terminated after the first two breaks. The first break occurred at 995,470 cycles and the second was at 2,594,840 cycles. Fatigue data from these tests were combined with data collected by the US Steel Corporation (Lucht and Donecker, 1977). The S/N diagram shown in Figure 7 includes both the US Steel data and the WHOI results. The same data analysis techniques used to produce the S/N diagram for the weldless sling links and safety shackles were also used for the wire rope S/N diagram.

One difference between the test results obtained for shackles and links and those accumulated for various wire rope tests is that the mean tension for the shackle and link tests were actually close to 4000 pounds. The adjustments made to the test amplitudes using

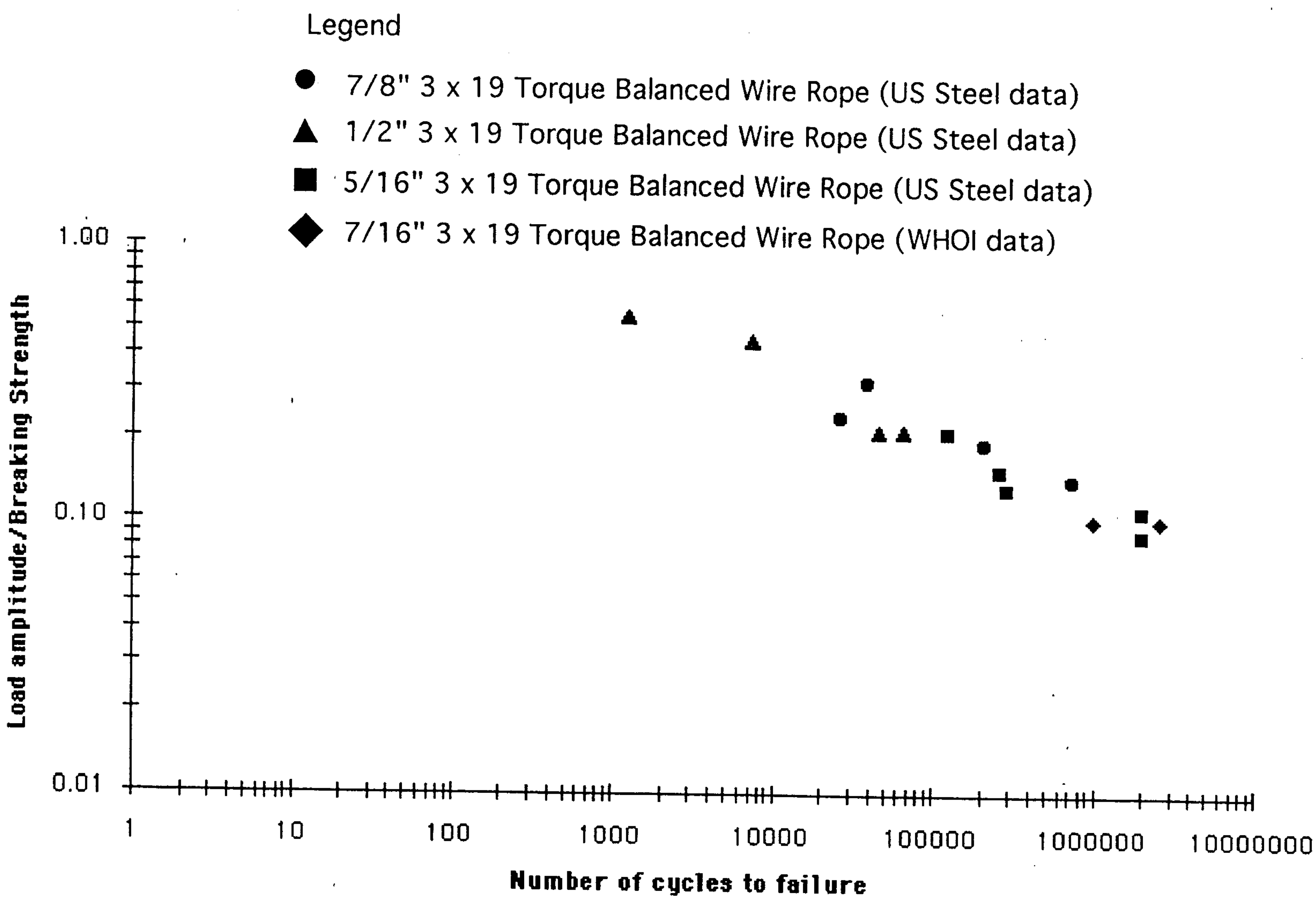


Figure 7. S/N diagram for 3 x 19 torque balanced wire rope. Load amplitude is an effective amplitude based on a mean tension of 4000 pounds.

equation 1 were small. However, the wire tests had mean tensions that ranged from 1800 to 19,500 pounds. It is unclear whether applying the same analysis technique used for the shackle and link data is appropriate for the collective wire rope data. We have, therefore, produced two S/N curves for the wire rope. The S/N diagram in Figure 7 uses effective load amplitudes of the various tests based on equation 1. Figure 8 is an S/N diagram using the same data but with the actual load amplitude from the specific tests.

Section V: Summary

Cyclic fatigue testing of in-line mooring components revealed several potential weak links and helped to specify the type of hardware used on the WHOI surface mooring deployed in the Arabian Sea in October 1994 and April 1995. The cyclic fatigue tests conducted as part of the Arabian Sea mooring design effort were as complete as time and funding permitted. Since all tests were conducted in a dry environment one needs to be cautious when applying these results to subsurface applications where corrosion fatigue can be an important factor. It is known that corrosion can reduce the fatigue strength by as much as half (Collins, 1993). Use of a factor of safety between predicted loads and actual component performance helps to offset uncertainties about actual loading and the effects of corrosion.

The use of shot peening mooring hardware, in particular safety chain shackles, was tested as an external treatment to improve component fatigue characteristics. The results of these tests indicated that the shot peened shackles had fatigue properties that were significantly better than non-shot peened shackles. Based on these results shot peened shackles were used throughout the WHOI surface mooring. By utilizing shot peening, shackle size did not have to be increased to acquire better fatigue properties at the expected loads. Larger shackles would have meant costly modifications to existing instrument load cages so as to accommodate their larger dimensions. Had a larger size shackle been needed both financial and design considerations would have suffered. A larger size component would have been more costly and would have weighed more which would have reduced the load carrying capacity of the mooring.

The superior performance of the weldless end links during the fatigue tests resulted in their replacing weldless sling links (also known as pear rings) throughout the Arabian Sea mooring. Tests on wire rope reinforced the need for careful adherence to swaging

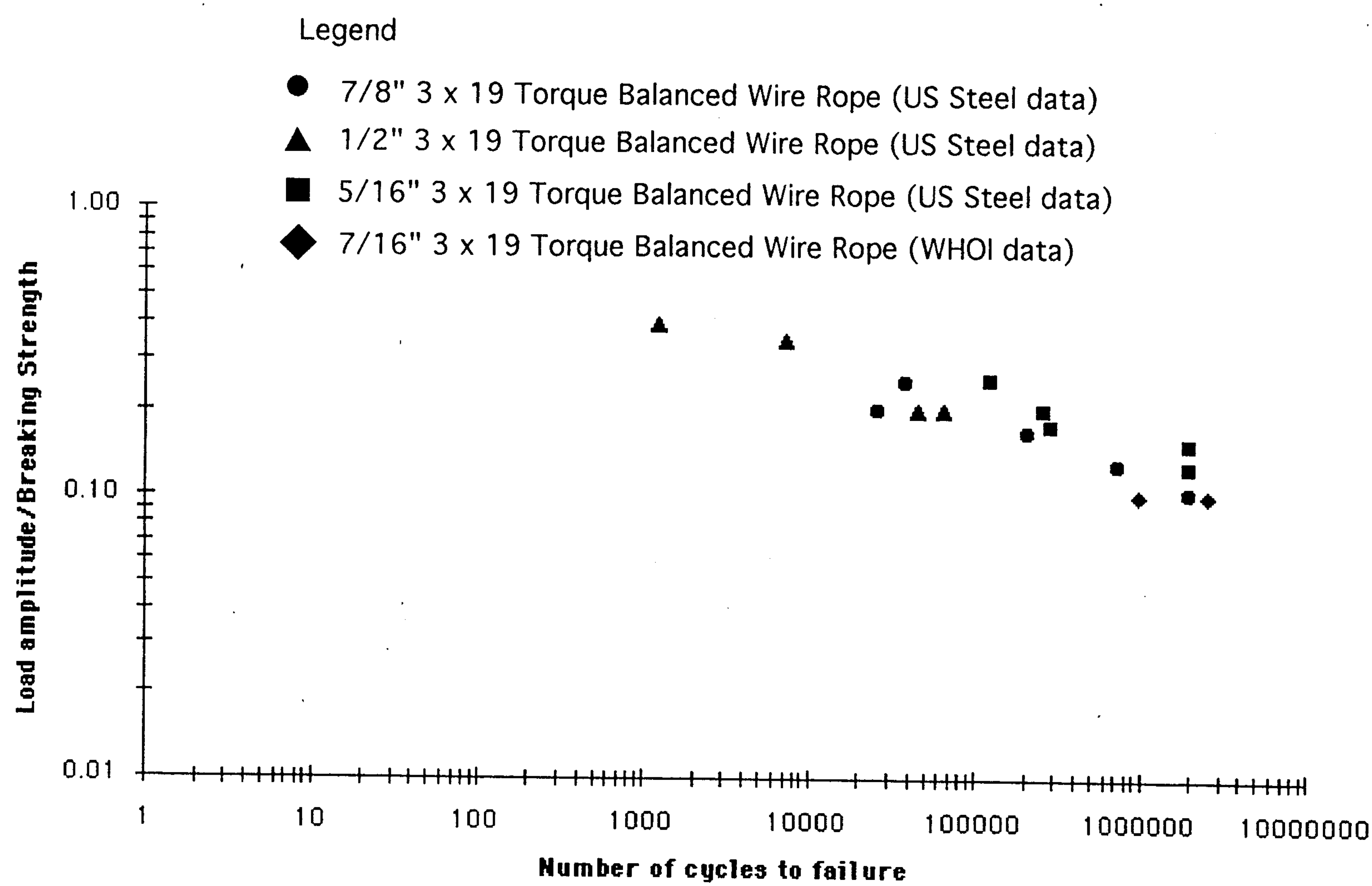


Figure 8. S/N diagram for 3 x 19 torque balanced wire rope. Load amplitude is the actual amplitude used during the cyclic testing.

specifications. Chain testing indicated that it was adequate for use on the Arabian Sea mooring.

The testing of VMCM load cages was particularly revealing. Loosely defined welding specifications coupled with a marginal end bale design resulted in fabricated products that did not perform well during the fatigue tests. Welding techniques and procedures were reviewed and a revised set of specifications were written. Two test cages fabricated with the new welding specification and with a modified end bale design were tested. The test cages performed well during the cyclic fatigue tests. All existing VMCM cages used on the WHOI Arabian Sea mooring were retrofitted with the modified end bale and all welds were brought up to the new specifications. All new fabrication of cages and strength members incorporated the new end bale and revised welding specifications.

The fatigue test results from shackles, and sling links were compiled to generate a S/N diagram that can be used in conjunction with future design efforts. In addition the wire rope tests results were compiled with historical wire rope data from US Steel to generate a S/N diagram for torque balanced 3x19 wire rope.

The information gained from these cyclic fatigue tests is applicable wherever hardware is subjected to dynamic loads. Any structure subject to surface waves, whether it be in a moored or towed application, is stressed both statically and dynamically. Little information is currently available about the fatigue characteristics of hardware of this type. Hardware manufacturers are concerned primarily with the static load carrying capability of their products. Static loads are, however, only one part of the problem. Rarely does a manufacturer conduct any fatigue analysis of their product for a duration typical of mooring applications. Failures can occur quite rapidly even when components are subjected to cyclic loads which may be considerably less than the component's ultimate strength. The magnitude of the static and dynamic loads, duration and component fatigue endurance are important considerations which cannot be ignored in the design process.

Acknowledgments

The authors wish to thank Mark Grosenbaugh and Nathan Ulrich for the guidance they provided during the fatigue testing program and for their assistance in the design of the Arabian Sea surface mooring. The cooperation of the WHOI rigging shop, under the direction of Dave Simoneau, in providing hardware and test samples is greatly appreciated. Special thanks are extended to Will Ostrom who oversaw the VMCM end bale redesign and took care of the logistics of getting samples to and from the testing lab. We sincerely thank Nancy Brink and Mary Ann Lucas for their help in preparing this report.

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Appendix 1: Fatigue Test Data

The data collected during the fatigue tests appear in Appendix 1. It has been grouped by component, size and loading. For example, 3/4" Crosby anchor shackles tested between 400 and 6800 pounds are separate from 3/4" Crosby anchor shackles tested between 400 and 7500 pounds. Within each group information about each component tested includes the maximum number of cycles attained, the condition of the component at the maximum number of cycles, and the specific test from which the data were obtained. For example, while testing VMCM cages there were a number of 3/4" anchor shackles in line as well. Some test data for the 3/4" anchor shackles will therefore indicate it originated from the cage tests.

5/8" Crosby Anchor Shackles			
Load Range:	400-7200 pounds		
Sample No.	Total Cycles	Condition	Test
1	438,380	Failed	5/8" Hardware Test 1.1
2	522,820	Intact	5/8" Hardware Test 1.1
3	231,710	Failed	5/8" Hardware Test 1.1
4	150,830	Failed	5/8" Hardware Test 1.1
5	307,770	Failed	5/8" Hardware Test 1.1
6	522,820	Intact	5/8" Hardware Test 1.1
7	262,520	Failed	5/8" Hardware Test 1.1
8	312,650	Failed	5/8" Hardware Test 1.1
9	330,500	Failed	5/8" Hardware Test 1.1
10	498,010	Failed	5/8" Hardware Test 1.1
11	400,430	Failed	5/8" Hardware Test 1.1
12	522,820	Intact	5/8" Hardware Test 1.1
13	522,820	Intact	5/8" Hardware Test 1.1
14	281,970	Failed	5/8" Hardware Test 1.1
15	329,720	Failed	5/8" Hardware Test 1.1
16	213,520	Failed	5/8" Hardware Test 1.1
17	155,670	Failed	5/8" Hardware Test 1.1
18	407,680	Failed	5/8" Hardware Test 1.1
19	522,820	Intact	5/8" Hardware Test 1.1
20-1	240,610	Failed	5/8" Hardware Test 1.1
21-1	186,800	Failed	5/8" Hardware Test 1.1
22	332,920	Failed	5/8" Hardware Test 1.1
23	522,820	Intact	5/8" Hardware Test 1.1
24	255,150	Failed	5/8" Hardware Test 1.1
25	157,700	Failed	5/8" Hardware Test 1.1
26	522,820	Intact	5/8" Hardware Test 1.1
27	515,810	Failed	5/8" Hardware Test 1.1
28	213,520	Failed	5/8" Hardware Test 1.1
29	467,640	Failed	5/8" Hardware Test 1.1
30	264,040	Failed	5/8" Hardware Test 1.1
31	522,820	Intact	5/8" Hardware Test 1.1
32	350,870	Failed	5/8" Hardware Test 1.1
4-1	371,990	Intact	5/8" Hardware Test 1.1
17-1	339,870	Failed	5/8" Hardware Test 1.1
21-1	336,020	Intact	5/8" Hardware Test 1.1
25-1	365,120	Intact	5/8" Hardware Test 1.1
28-1	258,510	Failed	5/8" Hardware Test 1.1
16-1	308,980	Failed	5/8" Hardware Test 1.1
3-1	291,110	Intact	5/8" Hardware Test 1.1

20-1	282,210	Intact	5/8" Hardware Test 1.1
24-1	267,670	Failed	5/8" Hardware Test 1.1
7-1	260,300	Failed	5/8" Hardware Test 1.1
30-1	226,490	Failed	5/8" Hardware Test 1.1
14-1	176,930	Failed	5/8" Hardware Test 1.1
5-1	149,410	Failed	5/8" Hardware Test 1.1
8-1	210170	Intact	5/8" Hardware Test 1.1
15-1	124,480	Failed	5/8" Hardware Test 1.1
9-1	192320	Intact	5/8" Hardware Test 1.1
22-1	115,160	Failed	5/8" Hardware Test 1.1
32-1	171950	Intact	5/8" Hardware Test 1.1
11-1	122390	Intact	5/8" Hardware Test 1.1
18-1	115140	Intact	5/8" Hardware Test 1.1
1-1	84440	Intact	5/8" Hardware Test 1.1
22-2	74740	Intact	5/8" Hardware Test 1.1
15-2	68620	Intact	5/8" Hardware Test 1.1
5-2	65640	Intact	5/8" Hardware Test 1.1
14-2	63920	Intact	5/8" Hardware Test 1.1
29-1	55180	Intact	5/8" Hardware Test 1.1
28-2	50790	Intact	5/8" Hardware Test 1.1
30-2	32290	Intact	5/8" Hardware Test 1.1
17-2	27280	Intact	5/8" Hardware Test 1.1
10-1	24810	Intact	5/8" Hardware Test 1.1
27-1	7010	Intact	5/8" Hardware Test 1.1
16-2	320	Intact	5/8" Hardware Test 1.1
5/8" Crosby Anchor Shackles			
Load Range:	400-6300 pounds		
Sample No.	Total Cycles	Condition	Test
1	313,210	Failed	5/8" Hardware Test 1.2
2	582,680	Intact	5/8" Hardware Test 1.2
3	442,290	Failed	5/8" Hardware Test 1.2
4	380,190	Failed	5/8" Hardware Test 1.2
5	112,280	Failed	5/8" Hardware Test 1.2
6	582,680	Intact	5/8" Hardware Test 1.2
7	299,440	Failed	5/8" Hardware Test 1.2
8	178,140	Failed	5/8" Hardware Test 1.2
9	136,170	Failed	5/8" Hardware Test 1.2
10	582,680	Intact	5/8" Hardware Test 1.2
11	582,680	Intact	5/8" Hardware Test 1.2

12	582,680	Intact	5/8" Hardware Test 1.2
13	442,290	Failed	5/8" Hardware Test 1.2
14	225,210	Failed	5/8" Hardware Test 1.2
15	196,680	Failed	5/8" Hardware Test 1.2
16	147,680	Failed	5/8" Hardware Test 1.2
17	226,150	Failed	5/8" Hardware Test 1.2
18	582,680	Intact	5/8" Hardware Test 1.2
19	582,680	Intact	5/8" Hardware Test 1.2
20	404,920	Failed	5/8" Hardware Test 1.2
21	572,790	Failed	5/8" Hardware Test 1.2
22	582,680	Intact	5/8" Hardware Test 1.2
23	165,480	Failed	5/8" Hardware Test 1.2
24	582,680	Intact	5/8" Hardware Test 1.2
25	346,870	Failed	5/8" Hardware Test 1.2
26	158,010	Failed	5/8" Hardware Test 1.2
27	178,700	Failed	5/8" Hardware Test 1.2
28	537,130	Failed	5/8" Hardware Test 1.2
29	582,680	Intact	5/8" Hardware Test 1.2
30	158,910	Failed	5/8" Hardware Test 1.2
31	456,910	Failed	5/8" Hardware Test 1.2
32	367,610	Failed	5/8" Hardware Test 1.2
5-1	190,940	Failed	5/8" Hardware Test 1.2
9-1	292,420	Failed	5/8" Hardware Test 1.2
16-1	154,240	Failed	5/8" Hardware Test 1.2
26-1	68,350	Failed	5/8" Hardware Test 1.2
30-1	423,770	Intact	5/8" Hardware Test 1.2
23-1	417,200	Intact	5/8" Hardware Test 1.2
8-1	374,070	Failed	5/8" Hardware Test 1.2
27-1	403,980	Intact	5/8" Hardware Test 1.2
15-1	380,220	Failed	5/8" Hardware Test 1.2
14-1	357,470	Intact	5/8" Hardware Test 1.2
17-1	356,530	Intact	5/8" Hardware Test 1.2
26-2	356,320	Intact	5/8" Hardware Test 1.2
7-1	283,240	Intact	5/8" Hardware Test 1.2
16-2	235,460	Failed	5/8" Hardware Test 1.2
6-1	154,170	Failed	5/8" Hardware Test 1.2
1-1	269,470	Intact	5/8" Hardware Test 1.2
25-1	235,810	Failed	5/8" Hardware Test 1.2
32-1	215,070	Intact	5/8" Hardware Test 1.2
4-1	202,490	Intact	5/8" Hardware Test 1.2
20-1	75,470	Failed	5/8" Hardware Test 1.2
9-2	154,090	Intact	5/8" Hardware Test 1.2
13-1	121,530	Failed	5/8" Hardware Test 1.2
3-1	140,390	Intact	5/8" Hardware Test 1.2

5/8" Anchor Shackles

31-1	125,770	Intact	5/8" Hardware Test 1.2
6-2	117,940	Intact	5/8" Hardware Test 1.2
20-2	102,290	Intact	5/8" Hardware Test 1.2
28-1	45,550	Intact	5/8" Hardware Test 1.2
16-3	45,300	Intact	5/8" Hardware Test 1.2
8-2	30,470	Intact	5/8" Hardware Test 1.2
13-2	18,860	Intact	5/8" Hardware Test 1.2
21-1	9,890	Intact	5/8" Hardware Test 1.2
15-2	5,780	Intact	5/8" Hardware Test 1.2

5/8" Shot Peened Crosby Anchor Shackles			
Load Range:	2000-6000 pounds		
Sample No.	Total Cycles	Condition	Test
1	1,207,640	Failed	Cages #2
2	5,000,000	Intact	Cages #2
3	2,727,410	Intact	Cages #2
4	2,727,410	Failed	Cages #2
1.1	555,210	Failed	Cages #2
1.2	3,237,150	Intact	Cages #2

3/4" Crosby Anchor Shackles			
Load Range:	400-6800 pounds		
Sample No.	Total Cycles	Condition	Test
3	1,165,930	Intact	Wire Rope #1
4	1,165,930	Intact	Wire Rope #1
5	813,970	Failed	Wire Rope #1
6	1,075,370	Intact	Wire Rope #1
8	506,210	Intact	Wire Rope #1
1	680,600	Failed	Cages #1
2	773,930	Failed	Cages #1
3	967,080	Intact	Cages #1
4	967,080	Intact	Cages #1
5	637,720	Intact	Cages #1
6	731,050	Intact	Cages #1
7	351,240	Failed	Cages #1
8	351,240	Intact	Cages #1
3/4" Crosby Anchor Shackles			
Load Range:	400-7500 pounds		
Sample No.	Total Cycles	Condition	Test
1	402,490	Intact	3/4" Hardware Test 1.6
2	183,140	Failed	3/4" Hardware Test 1.6
3	402,490	Intact	3/4" Hardware Test 1.6
4	402,490	Intact	3/4" Hardware Test 1.6
5	380,300	Intact	3/4" Hardware Test 1.6
6	354,120	Failed	3/4" Hardware Test 1.6
7	402,490	Intact	3/4" Hardware Test 1.6
8	402,490	Failed	3/4" Hardware Test 1.6
9	184,350	Failed	3/4" Hardware Test 1.6
10	313,590	Failed	3/4" Hardware Test 1.6
11	117,390	Failed	3/4" Hardware Test 1.6
12	402,490	Intact	3/4" Hardware Test 1.6
13	402,490	Intact	3/4" Hardware Test 1.6
14	163,590	Failed	3/4" Hardware Test 1.6
15	402,490	Intact	3/4" Hardware Test 1.6

16	141,120	Failed	3/4" Hardware Test 1.6
17	402,490	Intact	3/4" Hardware Test 1.6
18	402,490	Intact	3/4" Hardware Test 1.6
19	312,760	Failed	3/4" Hardware Test 1.6
20	402,490	Intact	3/4" Hardware Test 1.6
21	262,710	Failed	3/4" Hardware Test 1.6
22	240210	Failed	3/4" Hardware Test 1.6
23	162700	Failed	3/4" Hardware Test 1.6
24	402490	Intact	3/4" Hardware Test 1.6
3/4" Crosby Anchor Shackles			
Load Range: 400-8800 pounds			
Sample No.	Total Cycles	Condition	Test
1	67,400		3/4" Hardware Test 1.5
2	170,090	Intact	3/4" Hardware Test 1.5
3	80,860	Failed	3/4" Hardware Test 1.5
4	170,090	Intact	3/4" Hardware Test 1.5
5	59,970	Failed	3/4" Hardware Test 1.5
6	170,090	Failed	3/4" Hardware Test 1.5
7	64,700	Failed	3/4" Hardware Test 1.5
8	139,700	Failed	3/4" Hardware Test 1.5
9	93,260	Failed	3/4" Hardware Test 1.5
10	170,090	Intact	3/4" Hardware Test 1.5
11	106,280	Failed	3/4" Hardware Test 1.5
12	161,860	Intact	3/4" Hardware Test 1.5
13	136,930	Failed	3/4" Hardware Test 1.5
14	170,090	Intact	3/4" Hardware Test 1.5
15	170,090	Intact	3/4" Hardware Test 1.5
16	170,090	Intact	3/4" Hardware Test 1.5
17	162,400	Failed	3/4" Hardware Test 1.5
18	170,090	Intact	3/4" Hardware Test 1.5
19	170,090	Intact	3/4" Hardware Test 1.5
20	170,090	Intact	3/4" Hardware Test 1.5
21	58,430	Failed	3/4" Hardware Test 1.5
22	170,090	Intact	3/4" Hardware Test 1.5
23	170,010	Failed	3/4" Hardware Test 1.5
24	162,400	Failed	3/4" Hardware Test 1.5
21-1	44,850	Intact	3/4" Hardware Test 1.5
5-1	68,730	Intact	3/4" Hardware Test 1.5
7-1	59,290	Intact	3/4" Hardware Test 1.5
1-1	21,150	Intact	3/4" Hardware Test 1.5

3/4" Crosby Chain Shackles			
Load Range:	400-6800 pounds		
Sample No.	Total Cycles	Condition	Test
1c	265,140	Intact	Wire Rope #1
2c	198,850	Intact	Wire Rope #1
3c	263,670	Failed	Wire Rope #1
4c	344,320	Intact	Wire Rope #1
5c	321,870	Failed	Wire Rope #1
6c	329,960	Intact	Wire Rope #1
7c	198850	Intact	Wire Rope #1
8c	221300	Intact	Wire Rope #1
9c	198850	Intact	Wire Rope #1
10c	198850	Intact	Wire Rope #1
11c	329960	Intact	Wire Rope #1
12c	344320	Intact	Wire Rope #1
3/4" Crosby Chain Shackles			
Load Range:	2000-6000		
Sample No.	Total Cycles	Condition	Test
1	1,456,790	Failed	Chain
1-1	2,972,720	Failed	Chain
1-2	570,490	Intact	Chain
2	5,000,000	Intact	Chain
3	5,000,000	Intact	Chain
4	5,000,000	Intact	Chain
5	2,137,980	Failed	Chain
5-1	911,320	Failed	Chain
5-2	1,950,700	Intact	Chain
6	5,000,000	Intact	Chain
7	5,000,000	Intact	Chain
8	2,909,020	Failed	Chain
8-1	2,090,980	Intact	Chain

3/4" Crosby Chain Shackles			
Load Range:	400-10200 pounds		
Sample No.	Total	Condition	Test
1	258040	Intact	3/4" Hardware Test 1.4
2	90,680	Failed	3/4" Hardware Test 1.4
3	104,710	Failed	3/4" Hardware Test 1.4
4	165,220	Failed	3/4" Hardware Test 1.4
5	90,860	Failed	3/4" Hardware Test 1.4
6	91,040	Failed	3/4" Hardware Test 1.4
7	62,970	Failed	3/4" Hardware Test 1.4
8	138,170	Failed	3/4" Hardware Test 1.4
9	140,700	Failed	3/4" Hardware Test 1.4
10	91,040	Failed	3/4" Hardware Test 1.4
11	61,290	Failed	3/4" Hardware Test 1.4
12	166,090	Failed	3/4" Hardware Test 1.4
11 - I	84,010	Failed	3/4" Hardware Test 1.4
7 - I	75,200	Failed	3/4" Hardware Test 1.4
2 - I	106,090	Failed	3/4" Hardware Test 1.4
5 - I	115,530	Failed	3/4" Hardware Test 1.4
6 - I	167,000	Intact	3/4" Hardware Test 1.4
10 - I	149,580	Failed	3/4" Hardware Test 1.4
3 - I	83,590	Failed	3/4" Hardware Test 1.4
7-2	119,870	Intact	3/4" Hardware Test 1.4
8 -1	94,440	Failed	3/4" Hardware Test 1.4
9-1	117,340	Intact	3/4" Hardware Test 1.4
11-2	112,740	Intact	3/4" Hardware Test 1.4
4-1	92,820	Intact	3/4" Hardware Test 1.4
12-1	91,950	Intact	3/4" Hardware Test 1.4
3-2	69,740	Intact	3/4" Hardware Test 1.4
2-2	61,270	Intact	3/4" Hardware Test 1.4
5 - 2	51,650	Intact	3/4" Hardware Test 1.4
8 - 2	25,430	Intact	3/4" Hardware Test 1.4
10 - 2	17,420	Intact	3/4" Hardware Test 1.4

3/4" Shot Peened Crosby Chain Shackles				
Load Range:	2000-6000			
Sample No.	Total Cycles	Condition	Test	
1 SP	5,000,000	Intact	Chain	
2 SP	5,000,000	Intact	Chain	
3 SP	5,000,000	Intact	Chain	
4 SP	5,000,000	Intact	Chain	
5 SP	5,000,000	Failed	Chain	
6 SP	5,000,000	Intact	Chain	
7 SP	5,000,000	Intact	Chain	
8 SP	5,000,000	Intact	Chain	
Intact Components Tested Further				
1 SP	10,000,000	Intact	Cages #2	
2 SP	10,000,000	Intact	Cages #2	
3 SP	10,000,000	Intact	Cages #2	
4 SP	10,000,000	Intact	Cages #2	
5 SP	7,727,410	Intact	Cages #2	
7 SP	7,727,410	Intact	Cages #2	
Further Testing December 94				
1SP	14,000,000	Intact	Dec-94	
2SP	14,000,000	Intact	Dec-94	
3SP	14,000,000	Intact	Dec-94	
4SP	14,000,000	Intact	Dec-94	

5/8" Crosby Weldless Sling Links			
Load Range:	400-7200 pounds		
Sample No.	Total Cycles	Condition	Test
1a	35320	Failed	5/8" Hardware Test 1.1
3a	32560	Failed	5/8" Hardware Test 1.1
5a	35520	Failed	5/8" Hardware Test 1.1
7a	34560	Failed	5/8" Hardware Test 1.1
9a	29660	Failed	5/8" Hardware Test 1.1
11a	26560	Failed	5/8" Hardware Test 1.1
13a	21250	Failed	5/8" Hardware Test 1.1
15a	38280	Failed	5/8" Hardware Test 1.1
17a	34950	Failed	5/8" Hardware Test 1.1
19a	31020	Failed	5/8" Hardware Test 1.1
21a	37600	Failed	5/8" Hardware Test 1.1
23a	32670	Failed	5/8" Hardware Test 1.1
25a	34250	Failed	5/8" Hardware Test 1.1
27a	34370	Failed	5/8" Hardware Test 1.1
29a	32490	Failed	5/8" Hardware Test 1.1
31a	46550	Failed	5/8" Hardware Test 1.1
13a-1	35180	Failed	5/8" Hardware Test 1.1
11a-1	29870	Intact	5/8" Hardware Test 1.1
9a-1	26770	Intact	5/8" Hardware Test 1.1
19a-1	25410	Intact	5/8" Hardware Test 1.1
29a-1	23940	Intact	5/8" Hardware Test 1.1
3a-1	23870	Intact	5/8" Hardware Test 1.1
23a-1	23760	Intact	5/8" Hardware Test 1.1
25a-1	22180	Intact	5/8" Hardware Test 1.1
27a-1	22060	Intact	5/8" Hardware Test 1.1
7a-1	21870	Intact	5/8" Hardware Test 1.1
17a-1	21480	Intact	5/8" Hardware Test 1.1
1a-1	21110	Intact	5/8" Hardware Test 1.1
5a-1	20910	Intact	5/8" Hardware Test 1.1
21a-1	18830	Intact	5/8" Hardware Test 1.1
15a-1	18150	Intact	5/8" Hardware Test 1.1
31a-1	9880	Intact	5/8" Hardware Test 1.1
5/8" Crosby Weldless Sling Links			
Load Range:	400-6300 Pounds		
Sample No.	Total Cycles	Condition	Test

1a	47330	Failed	5/8" Hardware Test 1.2
3a	59210	Failed	5/8" Hardware Test 1.2
5a	54810	Failed	5/8" Hardware Test 1.2
7a	43290	Failed	5/8" Hardware Test 1.2
9a	106090	Failed	5/8" Hardware Test 1.2
11a	35450	Failed	5/8" Hardware Test 1.2
13a	50980	Failed	5/8" Hardware Test 1.2
15a	74060	Failed	5/8" Hardware Test 1.2
17a	40980	Failed	5/8" Hardware Test 1.2
19a	42850	Failed	5/8" Hardware Test 1.2
21a	53020	Failed	5/8" Hardware Test 1.2
23a	37030	Failed	5/8" Hardware Test 1.2
25a	44120	Failed	5/8" Hardware Test 1.2
27a	126400	Failed	5/8" Hardware Test 1.2
29a	55900	Failed	5/8" Hardware Test 1.2
31a	41380	Failed	5/8" Hardware Test 1.2
11a-1	41940	Failed	5/8" Hardware Test 1.2
23a-1	62600	Failed	5/8" Hardware Test 1.2
17a-1	29280	Failed	5/8" Hardware Test 1.2
31a-1	47090	Failed	5/8" Hardware Test 1.2
19a-1	40870	Failed	5/8" Hardware Test 1.2
7a-1	29720	Failed	5/8" Hardware Test 1.2
25a-1	42260	Failed	5/8" Hardware Test 1.2
1a-1	74050	Intact	5/8" Hardware Test 1.2
13a-1	59680	Failed	5/8" Hardware Test 1.2
21a-1	55640	Failed	5/8" Hardware Test 1.2
5a-1	66570	Intact	5/8" Hardware Test 1.2
29a-1	65480	Failed	5/8" Hardware Test 1.2
3a-1	65920	Failed	5/8" Hardware Test 1.2
17a-2	38210	Failed	5/8" Hardware Test 1.2
7a-2	36080	Failed	5/8" Hardware Test 1.2
15a-1	46280	Failed	5/8" Hardware Test 1.2
11a-2	43990	Intact	5/8" Hardware Test 1.2
15a-2	1040	Intact	5/8" Hardware Test 1.2
29a-2	Did Not Run		

3/4" Crosby Weldless Sling Links			
Load Range:	400-8800 Pounds		
Sample No.	Total Cycles	Condition	Test
1a	64780	Failed	3/4" Hardware Test 1.5
3a	68,550	Failed	3/4" Hardware Test 1.5
5a	60,800	Failed	3/4" Hardware Test 1.5
7a	128,700	Intact	3/4" Hardware Test 1.5
9a	49,440	Failed	3/4" Hardware Test 1.5
11a	63,670	Failed	3/4" Hardware Test 1.5
13a	55,760	Failed	3/4" Hardware Test 1.5
15a	49,830	Failed	3/4" Hardware Test 1.5
17a	86,570	Failed	3/4" Hardware Test 1.5
19a	81,620	Failed	3/4" Hardware Test 1.5
21a	64,500	Failed	3/4" Hardware Test 1.5
23a	70,980	Failed	3/4" Hardware Test 1.5
5a-1	67,900	Failed	3/4" Hardware Test 1.5
9a-1	31,420	Intact	3/4" Hardware Test 1.5
15a-1	78,110	Intact	3/4" Hardware Test 1.5
13a-1	72,940	Intact	3/4" Hardware Test 1.5
11a-1	65,030	Intact	3/4" Hardware Test 1.5
21a-1	58,490	Intact	3/4" Hardware Test 1.5
1a-1	16,080	Intact	3/4" Hardware Test 1.5
3a-1	60,150	Intact	3/4" Hardware Test 1.5
23a-1	57,720	Intact	3/4" Hardware Test 1.5
3/4" Crosby Weldless Sling Links			
Load Range:	400-7500 Pounds		
Sample No.	Total Cycles	Condition	Test
1	121,390	Failed	3/4" Hardware Test 1.6
2	161,300	Failed	3/4" Hardware Test 1.6
3	240,520	Intact	3/4" Hardware Test 1.6
4	240,520	Intact	3/4" Hardware Test 1.6
5	240,520	Intact	3/4" Hardware Test 1.6
6	66,800	Failed	3/4" Hardware Test 1.6
7	171,020	Failed	3/4" Hardware Test 1.6
8	105,910	Failed	3/4" Hardware Test 1.6
9	117,610	Failed	3/4" Hardware Test 1.6
10	131,780	Failed	3/4" Hardware Test 1.6
11	162,740	Failed	3/4" Hardware Test 1.6

12	192,310	Failed	3/4" Hardware Test 1.6
13	119,690	Failed	3/4" Hardware Test 1.6
14	104,750	Failed	3/4" Hardware Test 1.6
15	122,910	Failed	3/4" Hardware Test 1.6
16	119,130	Intact	3/4" Hardware Test 1.6
17	108,740	Intact	3/4" Hardware Test 1.6
18	79,220	Intact	3/4" Hardware Test 1.6
19	77,780	Intact	3/4" Hardware Test 1.6
20	69,500	Intact	3/4" Hardware Test 1.6
21	54,030	Intact	3/4" Hardware Test 1.6
22	48210	Intact	3/4" Hardware Test 1.6
23	29860	Intact	3/4" Hardware Test 1.6
3/4" Crosby Weldless Sling Links			
Load Range:	400-10200 pounds		
Sample No.	Total Cycles	Condition	Test
1a	28270	Failed	3/4" Hardware Test 1.4
3a	40170	Failed	3/4" Hardware Test 1.4
5a	39360	Failed	3/4" Hardware Test 1.4
7a	24090	Failed	3/4" Hardware Test 1.4
9a	37920	Failed	3/4" Hardware Test 1.4
11a	43650	Failed	3/4" Hardware Test 1.4
7a-1	26550	Failed	3/4" Hardware Test 1.4
1a-1	20970	Failed	3/4" Hardware Test 1.4
9a-1	82270	Failed	3/4" Hardware Test 1.4
5A - 1	18760	Failed	3/4" Hardware Test 1.4
3A - 1	10090	Failed	3/4" Hardware Test 1.4
11A - 1	20280	Failed	3/4" Hardware Test 1.4
1A - II	30740	Failed	3/4" Hardware Test 1.4
3A - 2	28596	Failed	3/4" Hardware Test 1.4
7A - II	24200	Failed	3/4" Hardware Test 1.4
7A - III	49460	Failed	3/4" Hardware Test 1.4
5A - 2	28160	Failed	3/4" Hardware Test 1.4
11A -2	24830	Failed	3/4" Hardware Test 1.4
3A - 3	48920	Failed	3/4" Hardware Test 1.4
5A - 3	28800	Failed	3/4" Hardware Test 1.4
11A - 3	26560	Failed	3/4" Hardware Test 1.4
5A - 4	41330	Failed	3/4" Hardware Test 1.4
11A - 4	33330	Failed	3/4" Hardware Test 1.4
9A - 2	28170	Failed	3/4" Hardware Test 1.4
7A - 4	41720	Failed	3/4" Hardware Test 1.4

3A - 4	26290	Failed	3/4" Hardware Test 1.4
1A - 3	56560	Failed	3/4" Hardware Test 1.4
9A - 3	27700	Failed	3/4" Hardware Test 1.4
11A - 5	38530	Failed	3/4" Hardware Test 1.4
3A - 5	25870	Failed	3/4" Hardware Test 1.4
5A - 5	35530	Failed	3/4" Hardware Test 1.4
7A - 5	34410	Failed	3/4" Hardware Test 1.4
9A - 4	29380	Failed	3/4" Hardware Test 1.4
3A - 6	45370	Failed	3/4" Hardware Test 1.4
1A - 4	31570	Failed	3/4" Hardware Test 1.4
5A - 6	31020	Failed	3/4" Hardware Test 1.4
7A - 6	57610	Failed	3/4" Hardware Test 1.4
9A - 5	25250	Failed	3/4" Hardware Test 1.4
3A - 7	24080	Failed	3/4" Hardware Test 1.4
11a-6	70860	Intact	3/4" Hardware Test 1.4
5a-7	35080	Intact	3/4" Hardware Test 1.4
1a-5	40810	Intact	3/4" Hardware Test 1.4
9a-6	27350	Intact	3/4" Hardware Test 1.4
3a-8	8660	Intact	3/4" Hardware Test 1.4
1A-2	27030	Failed	3/4" Hardware Test 1.4

7/8" Crosby Weldless Endlinks				
Load Range:	2000-6000			
Sample No.	Total Cycles	Condition	Test	
1	5,000,000	Intact	Chain Test	
2	5,000,000	Intact	Chain Test	
3	5,000,000	Intact	Chain Test	
4	5,000,000	Intact	Chain Test	
5	5,000,000	Intact	Chain Test	
6	5,000,000	Intact	Chain Test	
7	5,000,000	Intact	Chain Test	
8	5,000,000	Intact	Chain Test	
Intact Components Tested Further				
1	10,000,000	Intact	Cage Test #2	
2	10,000,000	Intact	Cage Test #2	
3	10,000,000	Intact	Cage Test #2	
4	10,000,000	Intact	Cage Test #2	
5	Not Tested			
6	Not Tested			
7	Not Tested			
8	Not Tested			
Further Testing December 94				
1	14,000,000	Intact	Teledyne Brown Eng. Dec 94	
2	14,000,000	Intact	Teledyne Brown Eng. Dec 94	
3	14,000,000	Intact	Teledyne Brown Eng. Dec 94	
4	14,000,000	Intact	Teledyne Brown Eng. Dec 94	
5	Not Tested			
6	Not Tested			
7	Not Tested			
8	Not Tested			

3/4" System 3 Proof Coil Chain				
Load Range:	2000-6000			
Sample No.	Total Cycles	Condition	Test	
1	5,000,000	Intact	Chain Test	
2	5,000,000	Intact	Chain Test	
3	5,000,000	Intact	Chain Test	
4	5,000,000	Intact	Chain Test	

VMCM Cages with 3/4" Cage Rods			
Load Range:	400-6800 Pounds		
Sample No.	Total Cycles	Condition	Test
Cage 1	351,240	Failed	Cage Test #1
Cage 2	967,080	Failed	Cage Test #1
VMCM Cages with 3/4" Cage Rods and Gussets			
Load Range:	2000-6000 Pounds		
Sample No.	Total Cycles	Condition	Test
Cage 3	5,000,000	Intact	Cage Test#2
Cage 4	5,000,000	Intact	Cage Test #2

7/16" Wire Rope			
Load Range:	400-6800 pounds		
Sample No.	Total Cycles	Condition	Test
1	198,850	Failed	Wire Test #1
2	223,940	Failed	Wire Test #1
3	304,870	Failed	Wire Test #1
4	344,320	Failed	Wire Test #1
7/16" Wire Rope			
Load Range:	2000-6000 pounds		
Sample No.	Total Cycles	Condition	Test
1	995,470	Failed	Wire Test #2
2	2,594,840	Failed	Wire Test #2
3	2,594,840	Intact	Wire Test #2
4	2,594,840	Intact	Wire Test #2

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16. Abstract (Limit: 200 words)

The Arabian Sea is strongly forced by monsoon winds. Surface moorings deployed in the Arabian Sea are exposed to high winds and large waves. The waves, generated by strong wind events, impose a dynamic load on all mooring components. The dynamic cycling of mooring components can be so severe that ultimate strength considerations are superseded by the fatigue properties of the standard hardware components.

Concerns about all in-line mooring components and their fatigue endurance dictated the need for an independent series of cyclic fatigue tests. The components tested included shackles of various sizes and configurations, wire rope, instrument cages, chain, and a variety of interconnecting links such as weldless sling links and end links. The information gained from these tests was used in the design of the surface moorings deployed in the Arabian Sea by the Upper Ocean Processes group of the Woods Hole Oceanographic Institution.

The results of the cyclic fatigue tests conducted in support of the Arabian Sea surface mooring design effort are presented in this report. Recommendations are made with regard to all in-line components for surface moorings where dynamic conditions might be encountered for extended periods. The fatigue test results from shackles, and sling links were compiled to generate an S/N diagram where the cyclic stress amplitude is plotted versus the number of cycles to failure. In addition, the wire rope test results were compiled with historical wire rope data from US steel to generate a S/N diagram for torque balanced 3x19 wire rope. These results can be used in conjunction with future design efforts.

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